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(6) **DYNAMIC ENVIRONMENTAL QUALIFICATION TECHNIQUES**

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(12) 42

Papers presented at the 48th Structures and Materials Panel Meeting, Williamsburg VA, USA, April 1979.

[illegible]

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PREFACE

Dynamic qualification test procedures must be applied for proving the safety and reliability of aircraft and spacecraft structures, and for determining the resistance of equipment to the effects of induced environments peculiar to military operations and requirements. This publication contains three papers which have been presented as pilot papers to the Ad Hoc Group on "Dynamic Environmental Qualification Techniques" during the Meeting of the Structures and Materials Panel in Williamsburg, USA, 2–6 April 1979.

The first paper by J.H.Wafford deals with the practical application of the MIL-STD 810c to USAF Aircraft Procurements. In the second paper by G.Haidl, C.Lodge and H.Zimmermann test experiences and problems in vibration qualification are presented and some means for improvement and recommendations are indicated. The third paper by B.W.Payne and G.H.F.Nayler, finally, is devoted to problems of civil aircraft equipment environmental qualification techniques.

All these papers provide insight into the wide area and problems of dynamic environmental qualification testing applied to civil and military airplanes, and to spacecraft structures also. It is believed to be a practical necessity for all NATO countries to attempt to formulate a common basis for dynamic environmental qualification requirements, and to incorporate related new technical findings in aircraft military standards.

H.FÖRSCHING
Chairman, Ad Hoc Group on
Dynamic Environmental
Qualification Techniques

A

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APPLICATION OF MIL-STD-810C
DYNAMIC REQUIREMENTS TO USAF AVIONICS PROCUREMENTS

by

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INTRODUCTION

This paper discusses briefly the development of the vibration requirements of MIL-STD-810C [1] and the application of these requirements to the procurement of avionics equipment. Although MIL-STD-810C was not made official until 1975, the Air Force promoted the use of random vibration testing and the tailoring of requirements at least 10 years prior to this time.

Even with the promotion of random vibration testing and the tailoring of the test levels, there is still Air Force equipment being procured and qualified to the older specifications with sinusoidal test levels. This is due primarily to the sheer number of black boxes being procured by the Air Force and the lack of direction provided to the project manager in developing meaningful environmental criteria and requirements. Due to this lack of direction, the project manager blindly applies any environmental tests that were run on a previous program or calls out MIL-STD-810, or worse, MIL-E-5400 as a design requirement for the avionics. This then ties the environmental requirement for the avionics to a test level and test method document. Granted, with this approach, we may provide a black box with significant environmental endurance, but have we provided the most cost effective installation by not considering the interface requirements and ways of reducing the environment at the equipment itself? This issue is not addressed in this paper but the Air Force is addressing this problem by providing a document that will guide the program manager in the environmental design as well as test area.

BACKGROUND

First I would like to go over briefly some of the background on the development of the dynamic requirements, mainly the random vibration requirements in Method 514 of MIL-STD-810C. I will show you how we have applied these requirements to both major weapon systems, i.e., F-15, F-16, and how the Air Force procures individual avionics for one or several aircraft.

DEVELOPMENT

In the development of the random vibration prediction technique, we recognized that we were dealing with a complex system and the input to the black box was not only dependent upon the source of vibration, but also on the installation and response of the black box in the aircraft. In the interest of keeping the prediction technique simple yet realistic, we tied the vibration to the source. This approach was also sellable to those who were use to the old sinusoidal tests, and not familiar with random vibration. We also were able to illustrate the numerous sources of random vibration for jet aircraft (Figure 1).

With this approach, random vibration techniques were developed that were flexible and source dependent. This provided us a way to depart from the rigid sinusoidal tests and interject realism into the testing.

In order to develop these new criteria, a data base was needed. One of the programs established to obtain a significant amount of this data was conducted at Wright-Patterson Air Force Base by the Air Force Flight Dynamics Laboratories and reported in references 2 and 3. Typical measurement locations are shown in Figure 2. The data were obtained basically at the attach points of the equipment items. Both internal and external noise measurements were also obtained.

The general trend of this data is as shown in Figure 3. The most severe vibration occurs during the transonic flight condition and at low altitude which generally represents the highest dynamic pressure. The formulae for the aerodynamically induced vibration of MIL-STD-810C were empirically derived by enveloping these worst case data for the transonic peaks [4].

From this data, the relationship of Figure 4 between the aerodynamic pressure and random vibration was developed. Two curves were developed; one for smooth surfaces and one for surfaces having protuberances such as antennas, speed brakes, chins, etc. This procedure tends to be conservative especially for low dynamic pressures, but does provide assurance that the vibration used in the test will be as severe as that encountered in service. There have, however, been special cases where this was not true.

The equations and definitions of Method 514.1, MIL-STD-810C, are contained in Figure 5 and Table 1, respectively [4][5]. There are two types of tests required in MIL-STD-810C - Functional and Endurance. The Functional level represents the maximum environment that the equipment will see in service; the Endurance level is an accelerated life test.

There are very few aircraft where the equation for jet engine noise induced vibration is the governing equation for establishing the functional test level. Normally the aerodynamic induced vibration is the more severe and establishes the maximum vibration level. Only when the structure is directly exposed to the jet exhaust will the jet engine noise equation be used to establish the test level.

The random vibration test spectrum used in MIL-STD-810C is shown in Figure 6. The low frequency end of the spectrum $0.04g^2/hz$ was arbitrarily established at this level and is attributed to major aircraft responses due to take off, landing, and gust. There was limited data available at the low frequencies when this standard was developed. In general, this value will be too severe for the functional test. The upper portion of the spectra, i.e., above 300 hz, is consistent with the forcing frequencies of the aerodynamic boundary layer and the jet noise spectra and the value for W_0 comes from the equation in the standard. I would like to point out that $0.04g^2/hz$ from 15 to 1000 hz is considered by the Air Force to be the minimum endurance test level for any equipment item. That is, no matter what the calculated endurance level, $0.04g^2/hz$ is the lowest acceptable value for USAF procurement purposes.

Similar work was also done in establishing the vibration and acoustic test for external stores [6][7]. The vibration test envelope for equipment located within the store and the equation used for predicting the test level are shown in Figure 7.

Figure 8 is the response envelope for the fully assembled store. In conjunction with this vibration test for the fully assembled store, an acoustical test method is also required. Method 515.2, Procedure II, is the test method for exposing the entire store to an acoustic environment. This test excites the higher frequencies in the store where the transfer of energy from a mechanical shaker is ineffective. Figure 9 is a typical setup of a fully assembled store vibration test.

This has been a very brief summary in the development of MIL-STD-810C. I would like, however, to point out that we are presently engaged in reformatting and updating MIL-STD-810C. Changes can be expected in the gunfire and shock methods as well as the vibration tests for cockpit and low frequency store environments. Hopefully, by the middle of the summer, much of the work will have been completed, and most of the problem areas in MIL-STD-810C should be cleared up by this revision.

APPLICATION

This section of the paper will show you how we have applied MIL-STD-810C to Air Force systems, both major weapon systems and individually procured equipment items.

MAJOR WEAPON SYSTEMS

As indicated earlier, the Air Force was using random vibration test requirements and the philosophy of tailoring the environment a long time before MIL-STD-810 was published. One of the first major systems to call out random vibration tests for qualification was the AWACS or E-3A aircraft (Figure 10). Much of the equipment was generally older and procured to sinusoidal specifications but the new equipment was required to be tested randomly, even in the radome and antenna.

The first major weapon system to require random vibration tests of all avionics was the F-15. Typical zones for vibration qualification are shown in Figure 11. Special zones (not shown) were also established for gunfire vibration tests. The levels for each zone were derived basically from measurements made by the contractor on a previous fighter aircraft and modified because of differences in structural configurations. A special environmental test document was established and applied to all of the avionics procured for the F-15.

Figure 12 shows the vibration zones for the first aircraft to use the MIL-STD-810C type predictions. The A-10 has the 30mm gun which was estimated to present a significant vibration environmental problem, especially in the forward portion of the aircraft. In general, the vibration from the gun blast has not been a problem. The vibration from the recoil forces, which we failed to consider in our early predictions and not taken into account in MIL-STD-810C, produced values at the gun harmonics that exceeded the levels estimated early in the program.

Another aircraft using MIL-STD-810C vibration levels is the F-16. The vibration zones are shown in Figure 13. Vibration measurements were obtained on the prototype aircraft and the environmental vibration test levels were adjusted based on this data. In most of the major weapon system programs, flight vibration measurements are required to verify the early vibration predictions and to update the environmental test documents established for that specific aircraft.

INDIVIDUALLY PROCURED AVIONICS

The previous discussion concentrated on major weapon systems. What happens when the avionics is procured by the Air Force to be put in one or even a number of different aircraft? If we are lucky, and the program manager does not take it upon himself to call out the environmental requirements by a blanket application or possibly exclude them altogether, we may be able to tailor the environmental requirements to the actual service environment of the avionics installation. If we know the aircraft into which the equipment is going, and its location in the aircraft, we may be able to use measured data. If the avionics is to be used in more than one aircraft, we take the maximum environmental levels, develop a composite vibration test envelope, and use that test envelope as the functional test level.

When measurements are not available and/or we are unsure of the installation location, we then use the prediction technique in MIL-STD-810C to establish the test values. If an avionics item has been previously qualified for utilization in another aircraft and the new installation environment is more severe, we have three options: Requalify, Protect the equipment, or Do Nothing. This is usually not a very palatable situation because Requalification may involve costly redesign for the avionics vendor. Protection normally involves structural changes, isolation, and/or relocation of the equipment item which the aircraft program office does not like. If we Do Nothing, we risk having a low reliability equipment item in our aircraft which will probably be a high cost maintenance item. The solution should be the most cost effective one, but may depend upon the program office with the most money.

I would like to point out that MIL-STD-810C is only a guide and is to be used as such, especially when other information is available.

Hopefully, I have provided you with some insight on the development of MIL-STD-810C requirements and how we apply them to our procurements. With the work now being done on the standard and the improvements being made, I am convinced that the dynamic test methods and procedures of MIL-STD-810C will form a firm foundation for NATO standardization.

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[5]	J. H. Wafford J. F. Dreher	Aircraft Equipment Random Vibration Test Criteria Based on Vibration Induced by Jet and Fan Engine Exhaust Noise, Shock and Vibration Bulletin No. 39, June 1973
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[7]	Allan G. Piersol	Digitek Corp., "Vibration and Acoustic Test Criteria for Captive Flight of Externally Carried Aircraft Stores," AFFDL-TR-71-158, December 1971

TABLE I

$K = 2.7 \times 10^{-8}$	EXTERNAL FLOW SMOOTH
$= 14 \times 10^{-8}$	EXTERNAL FLOW TURBULENT

q = AERODYNAMIC PRESSURE LBS/SQ FT

N = NUMBER OF MISSIONS (EQUIPMENT OR AIRCRAFT)

T = TEST TIME PER AXIS

D = DIAMETER OF ENGINE EXHAUST

V = VELOCITY OF ENGINE EXHAUST

R = DISTANCE, ENGINE EXHAUST EXIT TO EQUIPMENT

θ = ANGLE, R LINE AND EXHAUST AXIS

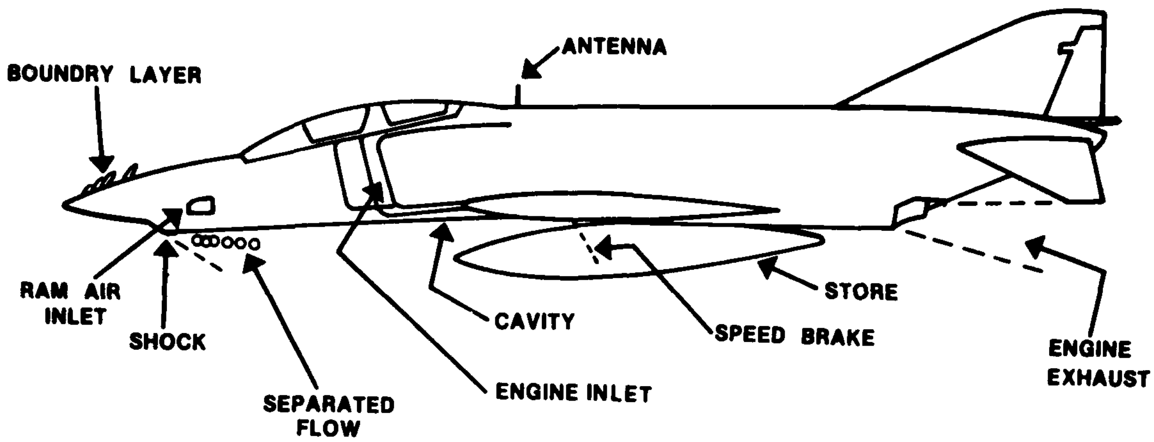


Fig.1 Typical sources of random vibration for fighter aircraft

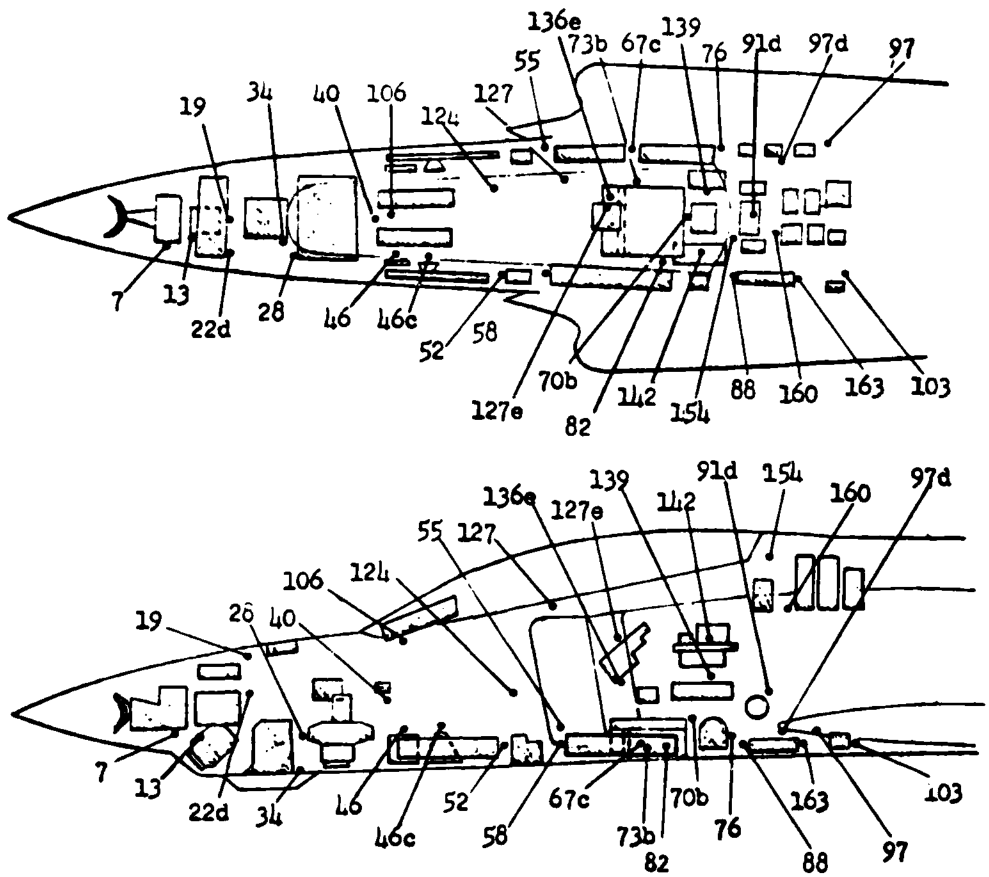


Fig.2 Accelerometer locations

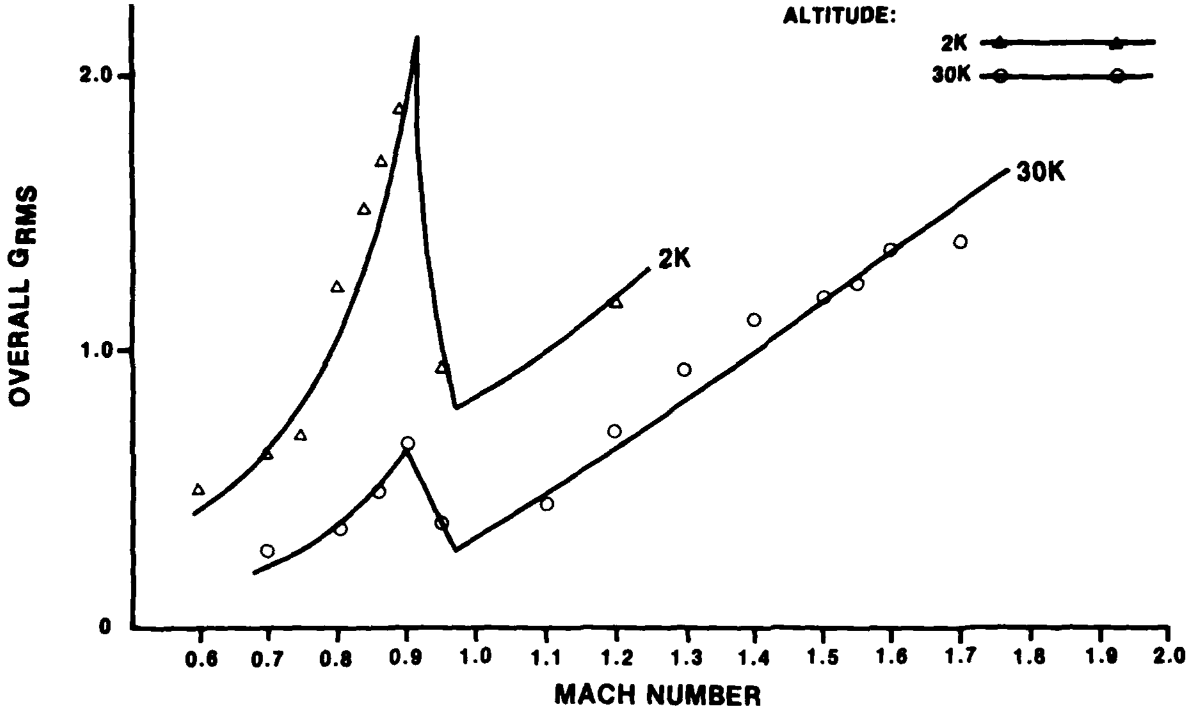


Fig.3 Structural vibration vs Mach number

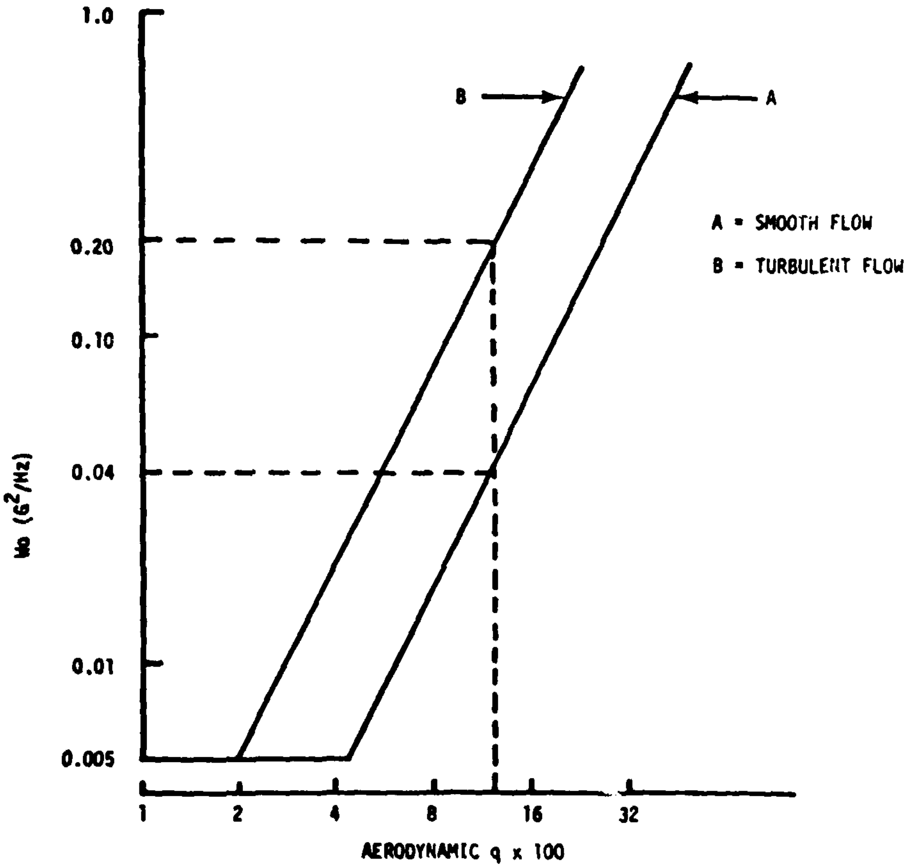


Fig.4 Vibration levels vs aerodynamic pressure (q)
for jet aircraft equipment

AERODYNAMIC INDUCED VIBRATION

FUNCTIONAL LEVEL $Wo = K(q_1)^2$

ENDURANCE LEVEL $Wo = K(q_2)^2(N/3T)^{1/4}$

JET ENGINE NOISE INDUCED VIBRATION

FUNCTIONAL LEVEL

$$Wo = (0.48\ \cos^2\theta/R)\left[D_C(V_C/1850)^3 + D_F(V_F/1850)^3\right]$$

ENDURANCE LEVEL

$$W_{O_E} = W_O(N/10T)^{1/4}$$

Fig.5 MIL-STD-810C equations

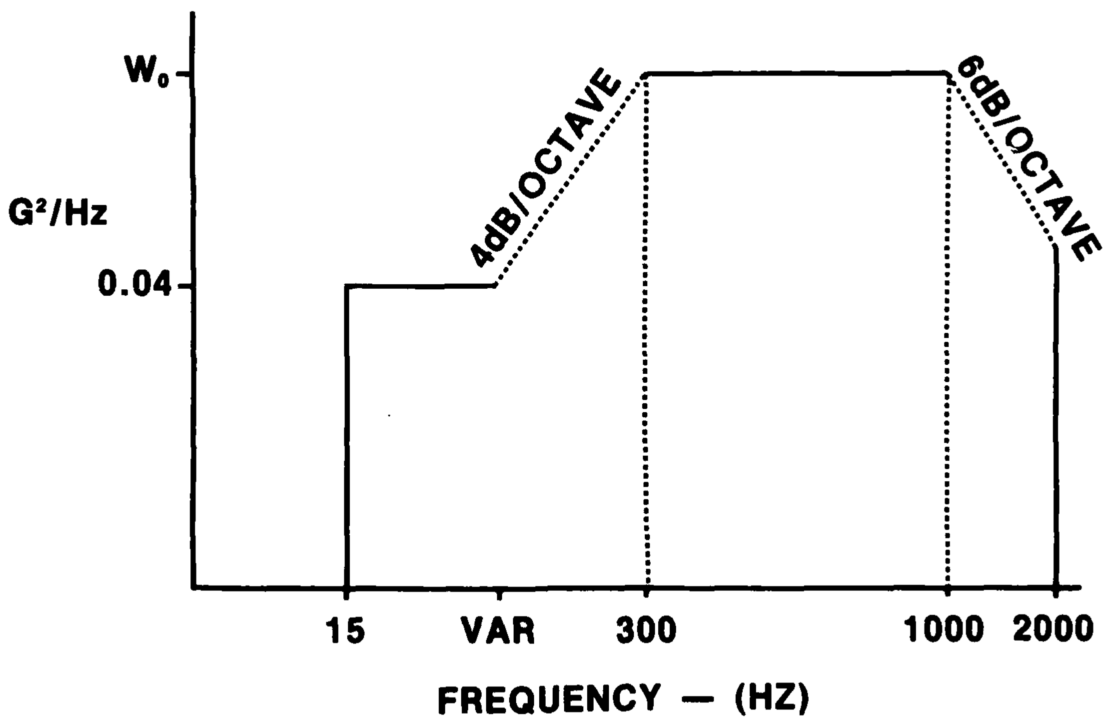
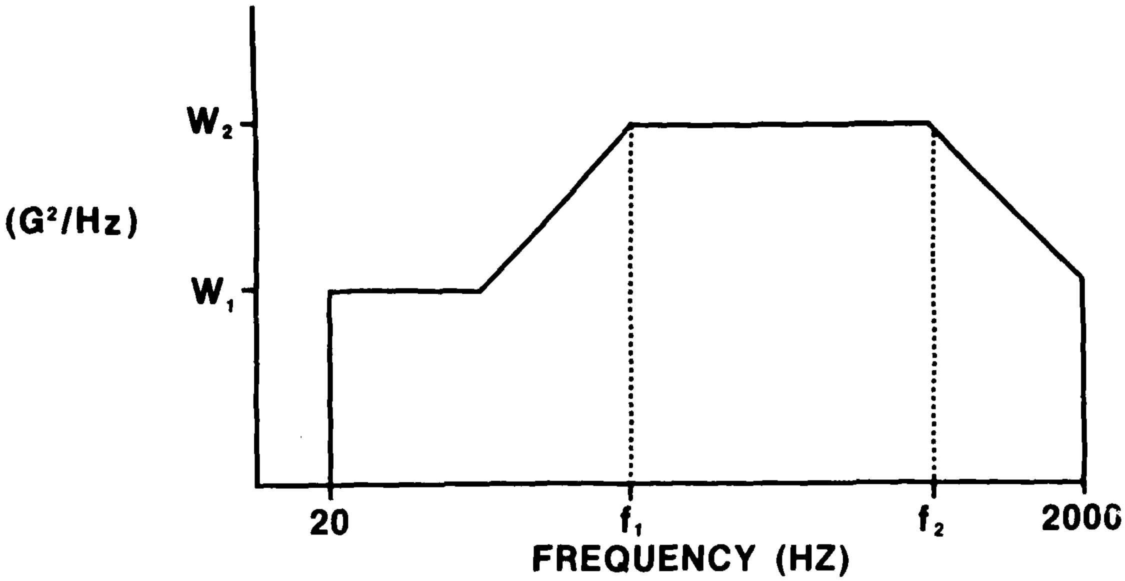


Fig.6 Random vibration envelope – jet aircraft



$$W_1 = (5)(10^{-3})(N/3T)^{1/4}$$
$$W_2 = (5)(10^{-5})\,(q/w)^2\,(N/3T)^{1/4}$$
$$f_1 = 10^5\,(t/R^2)\ \text{Hz}$$
$$f_2 = f_1 + 1000\ \text{Hz}$$

Fig.7 Random vibration envelope – equipment in external stores

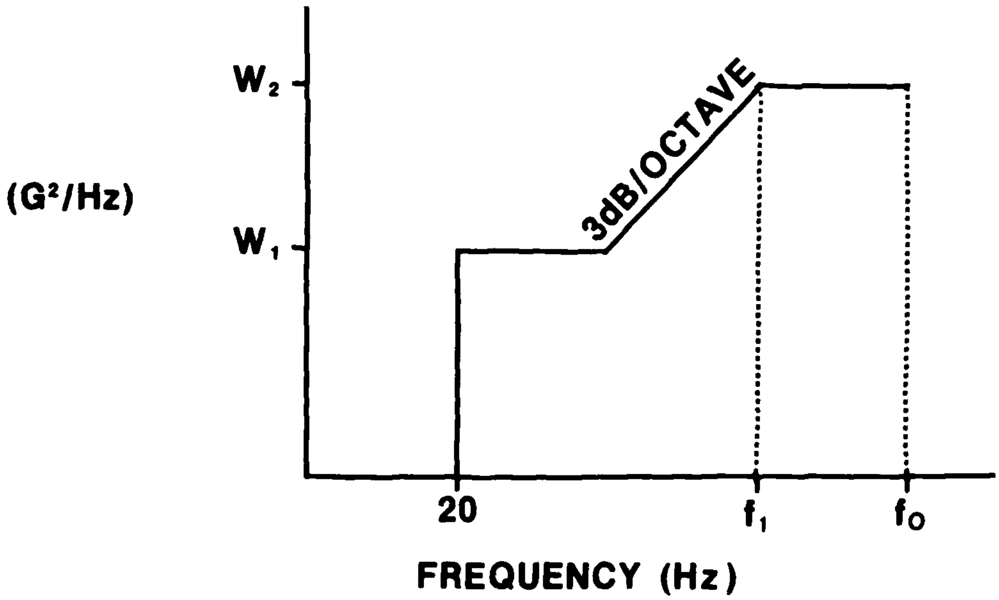


Fig.8 Random vibration envelope – assembled external stores

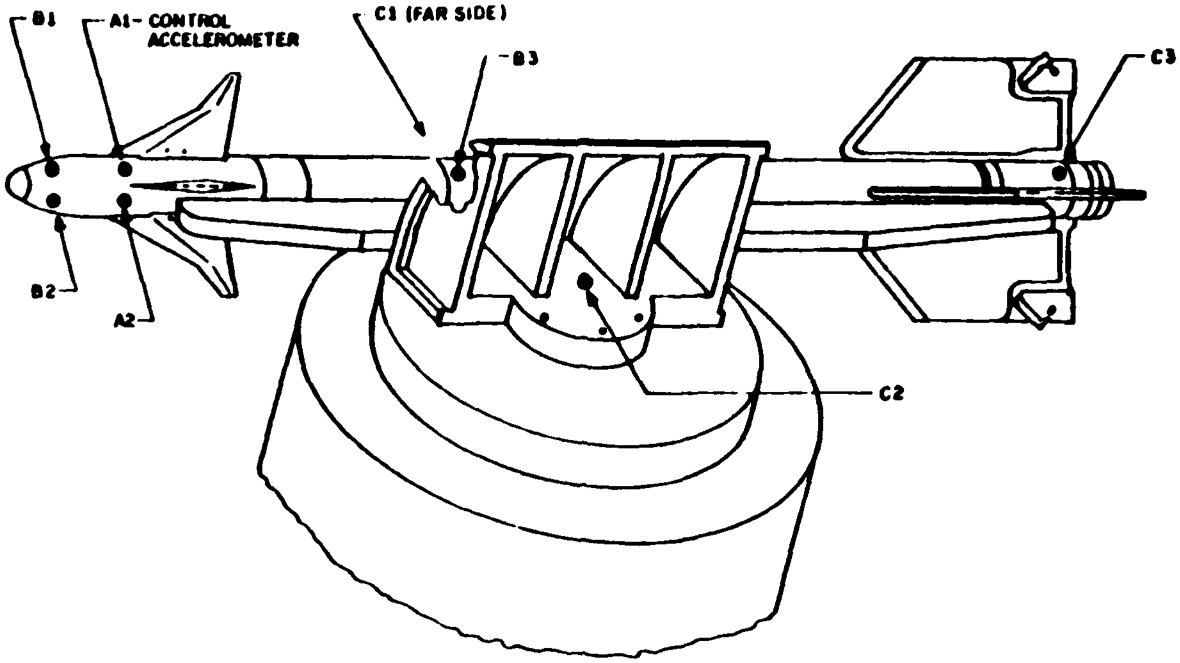


Fig.9 Fully assembled store test

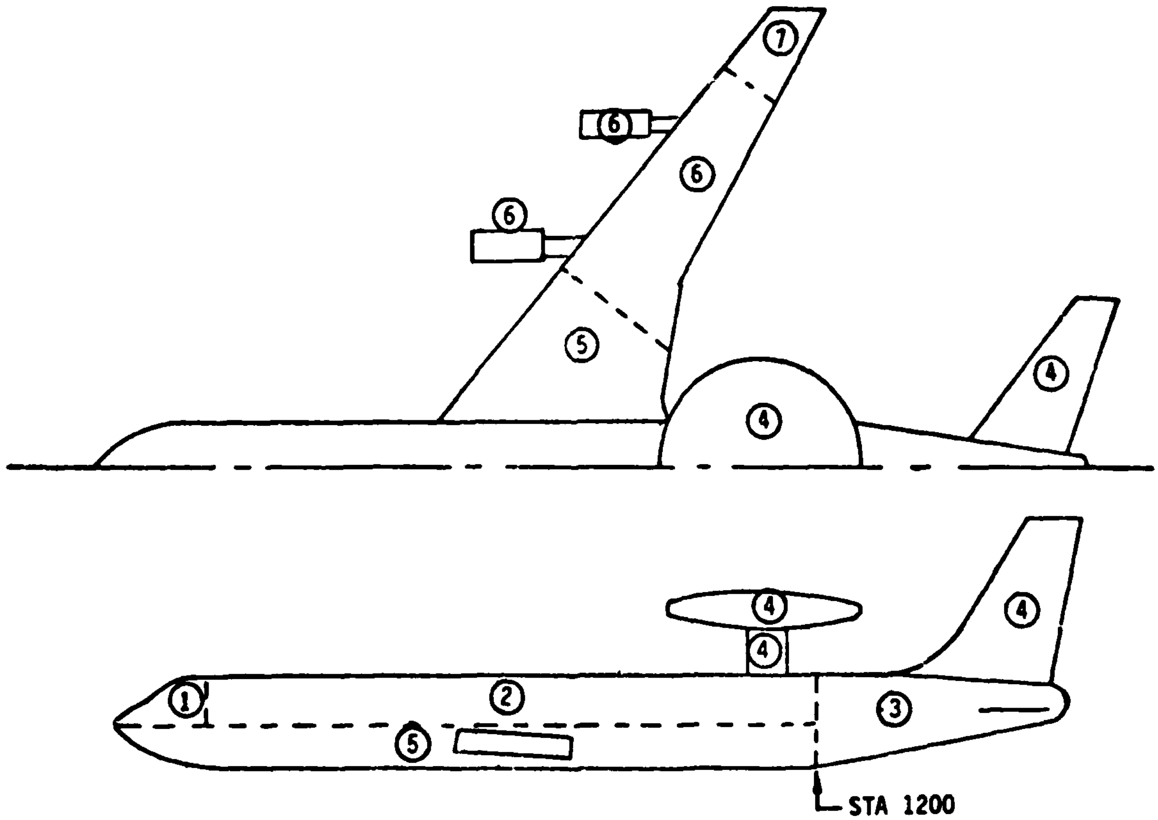


Fig.10 E-3A vibration zones

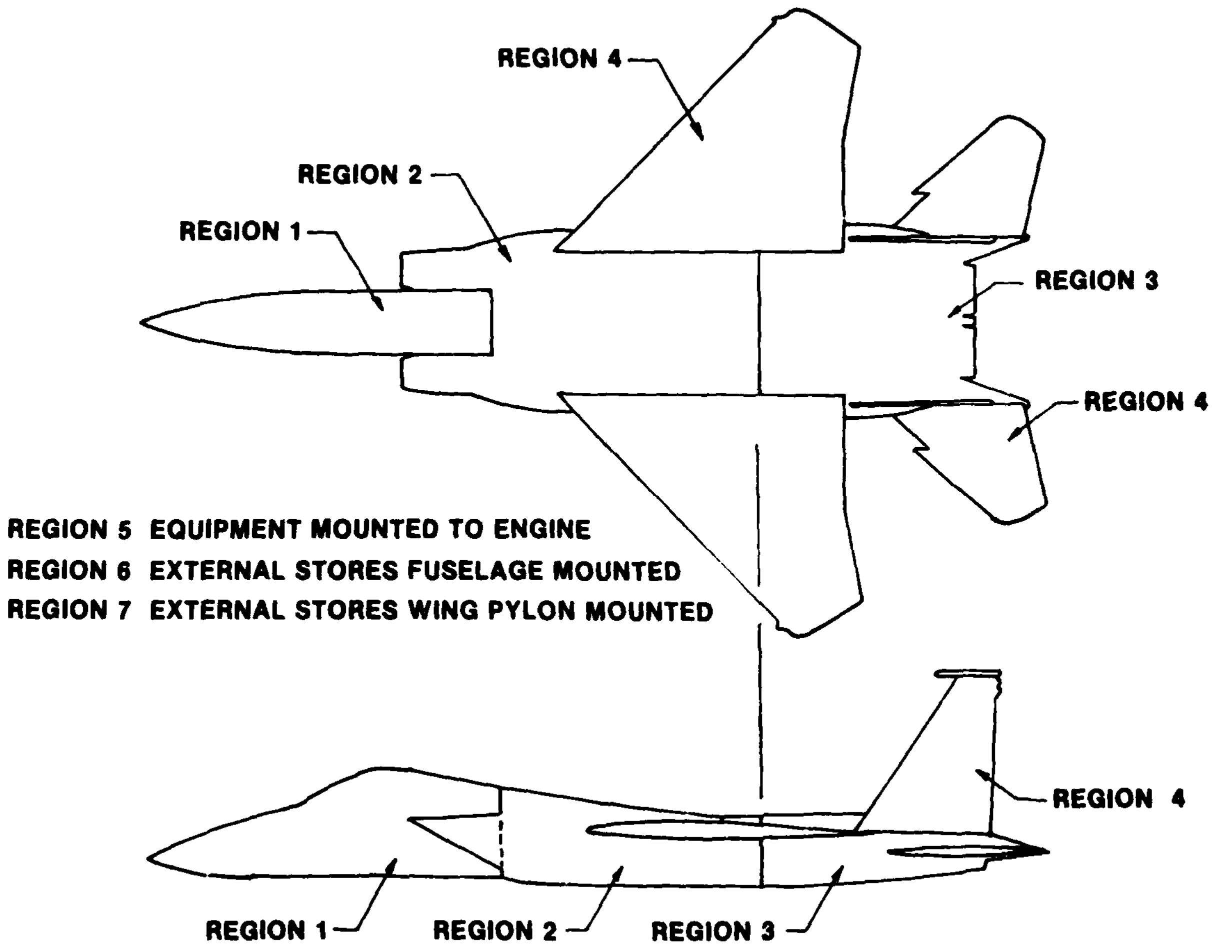


Fig.11 F-15 vibration zones

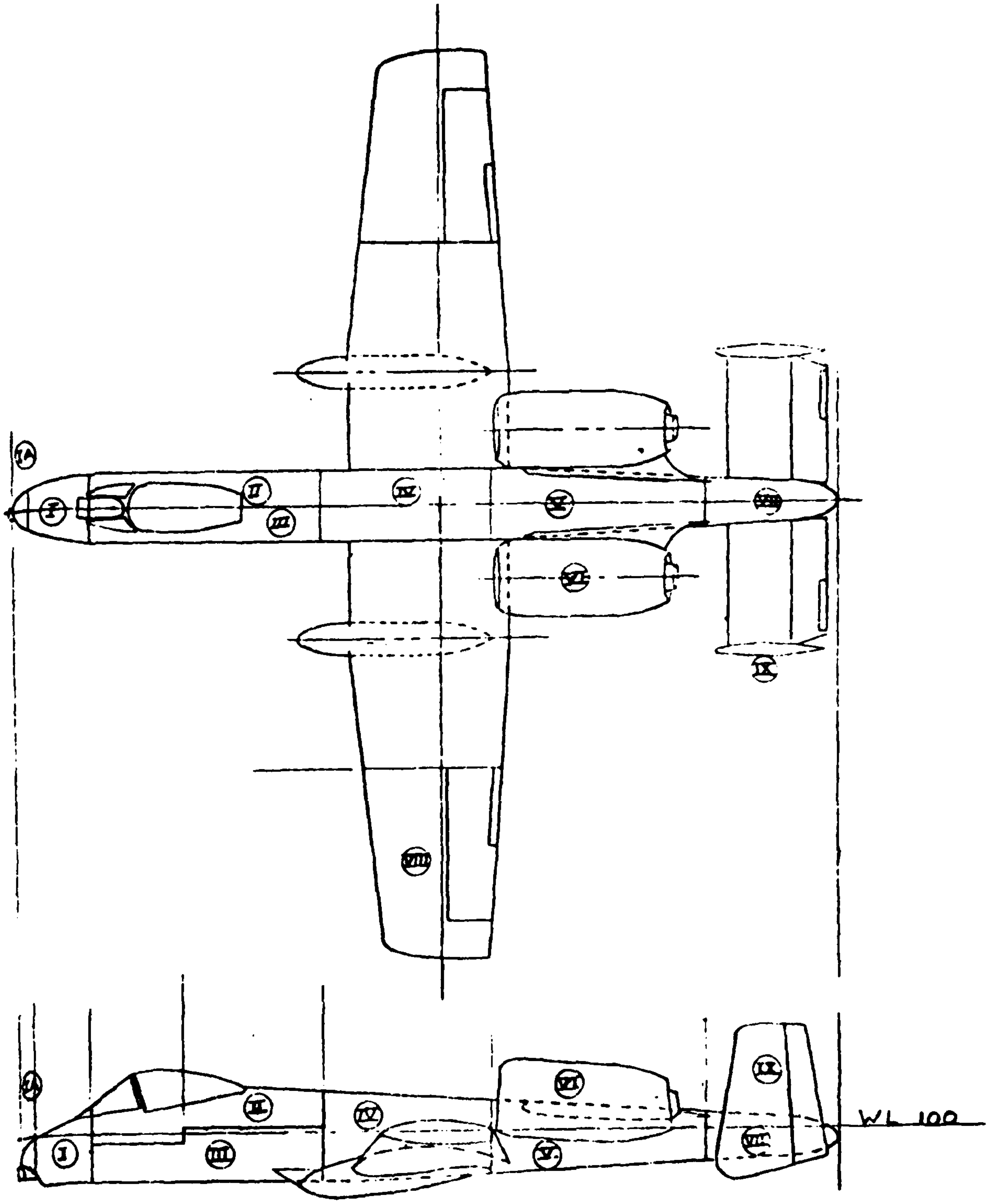


Fig.12 A-10 vibration zones

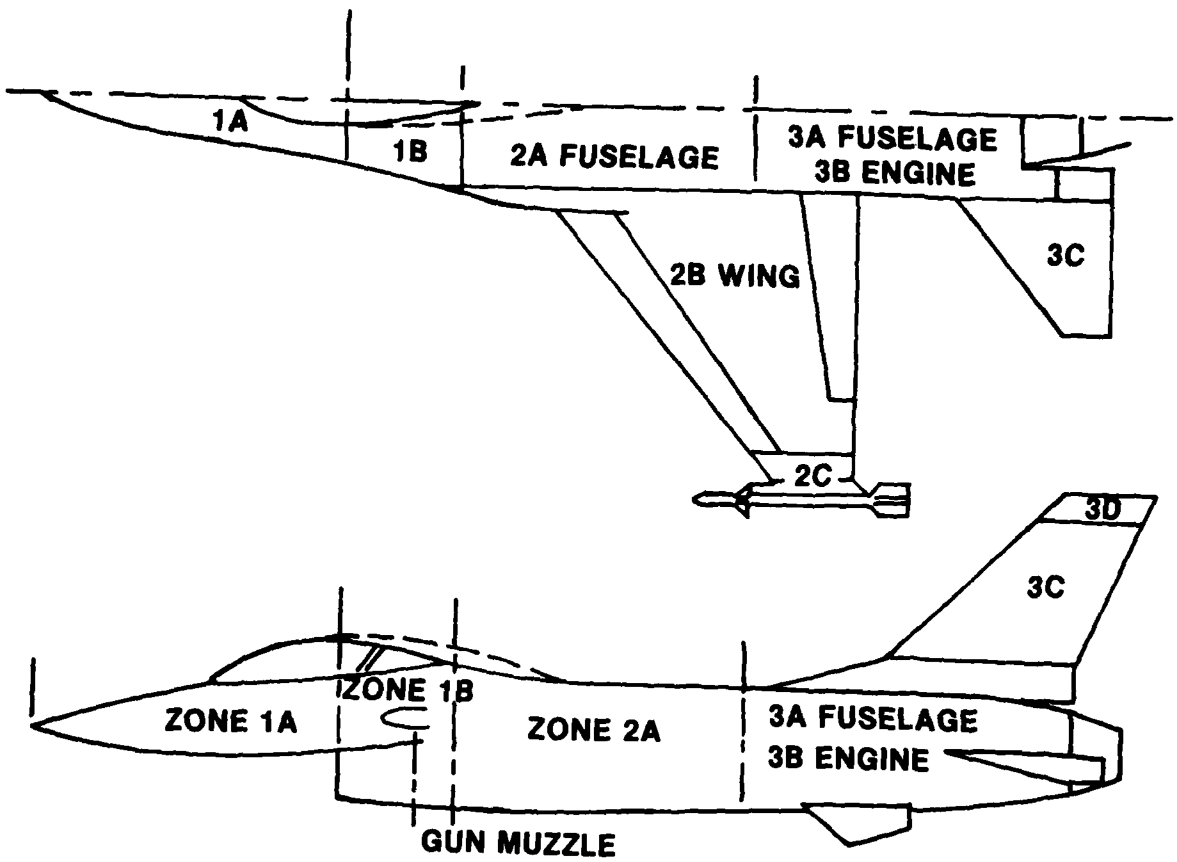


Fig.13 F-16 vibration zones

DYNAMIC ENVIRONMENTS AND TEST SIMULATION FOR QUALIFICATION OF AIRCRAFT EQUIPMENT AND EXTERNAL STORES

by

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INTRODUCTION

Equipment within an aircraft is exposed to a wide variety of dynamic environments during ground- and flight operations. Developing adequate qualification criteria, which take account of these manifold conditions is, at best, difficult. Many interesting investigations have concentrated on the task of realistic environment prediction for aircraft equipment and stores, and on improving the-state-of-the-art in understanding of related dynamic- and vibration phenomena and of contributing factors.

Useful methods of dynamic environment prediction are needed for any qualification. The qualification may be achieved either by analytical methods, or by considerations of analogy, or by adequate test evidence.

How to accumulate and to generalize information on the different dynamic environmental conditions, in order to be of practical use in qualification, is another challenge in engineering work.

Realistic development and successful application of appropriate procedures needs the complete background of information and basic philosophy.

1. BASIC AIMS AND PROCEDURES

The basic aim of all environmental qualification testing is to achieve confidence in aircraft equipment reliability and performance under conditions which will be encountered during service life. The procedure generally adopted to achieve this objective is to establish environmental test specifications, based upon real environments, but simplified for simulation, and call up sufficient exposure in rigs to demonstrate reliability and performance prior to flight.

The adequacy of this qualification procedure can be assessed in the short term, following prototype flight experience, by comparing measured with simulated environmental characteristics and in the long term, following service experience, by monitoring equipment reliability. It is quite clear, that success requires close co-operation between aircraft operators, airframe manufacturers and equipment suppliers at all stages of procurement and service.

Inevitably the rig test specifications must be a compromise between the real equipment environments and exposure times and those which can be economically represented in laboratories. These compromises are addressed in the National Standards which have formed the basis of formal qualification procedures over the last two decades. Significantly different specification requirements emerge,reflecting the difficulties involved in making this compromise.

Therefore, the proper application of any environmental specifications needs the background of basic philosophy and, as much as possible, the source of information from laboratory tests and inflight vibration measurements. The question of test realism is often the subject of considerable discussions especially when the equipment failed in the test. Without this background it is impossible to interpret test specifications and results correctly. Therefore systematic investigations and flight environmental surveys are of great help to support qualification work and to improve specifications where necessary. The better the knowledge of sources of excitation, transmission paths, dynamic system behaviour, the better the understanding and establishment of appropriate methods of prediction and test simulation. The intensive investigations, which formed the basis for the new MIL-Std.-810 C are a good example in this respect. However, they have also generated an increasing number of specification requirements which must be considered, when the extent of qualification evidence for a given case has to be established. A reasonable balance in qualification must be sought between necessary technical evidence and justifiable costs. This must be also compatible with the specific contractual basis.

It is our intention in the following presentation, to show the present situation in our countries, with particular emphasis on military applications and from the point of view of test specification users. Some specific examples of application experience are presented and some problem areas in qualification are reviewed. Possible means of improvement and recommendations for information exchange are given.

2. CURRENT STATUS AND PHILOSOPHY

Environmental qualification is generally based upon National- or nationally adopted standards, which aim to ensure adequate qualification by uniform and compatible procedures.

Considerable experience has been obtained during national and international aircraft programmes in the application of different standards like

British Standards	(i.e. Strikemaster, Harrier, Jaguar, Hawk)
French Standards	(i.e. Alpha Jet, Jaguar)
U.S. Standards and Spec's	(VJ 101, VAK 14i, F 104 G, TORNADO)

MIL STD 810B, METH. 514		EQUIPMENT INSTALLED IN AIRPLANES	
	RESONANCE SEARCH	ENDURANCE TEST	
TYPE	FREQUENCY SWEEP 5 - 2000 Hz (5 - 500 Hz)	RESONANCE DWELL AT EACH RESONANCE FREQUENCY (up to 4)	FREQUENCY SWEEP 5 - 2000 Hz (5 - 500 Hz)
LEVEL	REDUCED	DEPENDENT UPON EQUIPMENT LOCATION AND TEST CURVE	
TIME per AXIS	— · —	1/2 HOUR AT EACH RESONANCE	3 HOURS LESS DWELL TIME

BS 2G.100, P. 2, Cl. 218		EQUIPMENT INSTALLED IN AIRPLANES		
	RESONANCE SEARCH	ENDURANCE TEST		
			EITHER	OR: (OPTION)
TYPE	— · —	RESONANCE DWELL AT EACH RESON. FREQUENCY	DWELL TEST AT 20, 50, 150 Hz (OUTSIDE RE-SONANCES)	FREQUENCY SWEEP 3 - 150 Hz
LEVEL	— · —	DEPENDENT UPON EQUIPMENT LOCATION AND TEST CURVE		
TIME per AXIS	— · —	10 HOURS AT EACH RESONANCE	109 HOURS TOTAL	100 HOURS

FIG. 1 VIBRATION QUALIFICATION ACCORDING TO MIL-STD-810 B AND BS 2G.100

On particular projects, where the need has arisen (TSR 2, TCA*) additional testing requirements have been defined to cover special-to-type environments.

To our knowledge the U.S. standards are the most extensive requirements and their procedures and methods reflect the immense experience gained in the United States during flying of numerous military airplanes. They cover a wide variety of applications and they are frequently used in international aircraft programmes.

A wider interchangeability of equipment, qualified to different standards, is sometimes difficult, because of different requirements, procedures and philosophy. The introduction of more uniform internationally agreed standards (e.g. Nato Std. STANAG) is very desirable.

Concerning dynamic environmental features, vibration is the most important. This much is clear from the relatively high number of failures which occur during vibration tests and from the relatively high number of defects which are attributable to vibration in service operation. Most of this vibration qualification experience relates to sinusoidal testing. See Fig. 1 and 2.

These tests are more or less appropriate for equipment vibration environments which are dominated by engines, or by low frequency structural modes of the aircraft, or by other mechanical resonance phenomena. Nevertheless this sinusoidal procedure has been applied in the majority of equipment tests in the past. This procedure has been interpreted as ensuring a degree of robustness in equipment design, which will in turn promote reliability. It is interesting to see, that test amplitude levels are broadly similar in British and American Standard but that test frequency range and time, particulary endurance, vary to a remarkable degree.

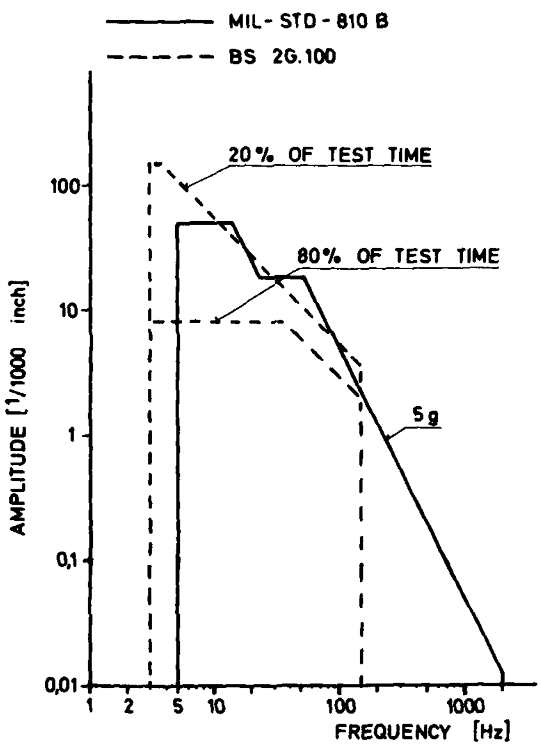

FIG. 2 TEST AMPLITUDES FOR EQUIPMENT HARD MOUNTED TO AIRCRAFT STRUCTURE

Better knowledge of real vibration environments has led to the introduction of random test requirements into the National Standards, which aim for greater realism in vibration qualification.

The differences in approach and test philosophy between U.S.-Standard and British Standard are indicated in Fig. 3. This figure shows a survey of characteristic details and differences for random test procedure and for "equipment installed in airplanes".

*) Tactical Combat Aircraft

MIL STD 810 C, METH. 514	EQUIPMENT INSTALLED IN AIRPLANES		
	FUNCTIONAL TEST 1 st PART	ENDURANCE TEST (no functional monitoring)	FUNCTIONAL TEST 2 nd PART
TYPE	BROADBAND RANDOM VIBRATION 15 - 2000 Hz		
LEVEL	DEPENDENT UPON EQUIPMENT LOCATION, max. AIRSPEED, INDUCED ENGINE VIBRATION, EQUIPMENT WEIGHT, TEST CURVE		
TIME per AXIS	1/2 HOUR	≥ 1 HOUR (provision for longer test time and equivalent level reduction)	1/2 HOUR

BS 3G. 100 PART 2 SECTION 3 SUBSECTION 3.1	EQUIPMENT INSTALLED IN AIRPLANES		
	INITIAL RESONANCE SEARCH	ENDURANCE BY RANDOM	FINAL RESONANCE SEARCH
TYPE	FREQUENCY SWEEP 10 - 1000 Hz	RANDOM VIBRATION 10 - 60 Hz 60 - 1000 Hz	FREQUENCY SWEEP 10 - 1000 Hz
LEVEL	DEPENDENT UPON EQUIPMENT LOCATION AND MOST SEVERE VIBRATION CATEGORY DEFINED BY FLIGHT CONDITIONS		
TIME per AXIS	—·—	SPECIAL PROCEDURE ACCOUNTING FOR ACCUMULATED MISSION TIME	—·—

FIG. 3 VIBRATION QUALIFICATION ACCORDING TO MIL-STD-810 C AND BS 3G.100

Both standards pay regard to the individual location of equipment within the A/C but they show a different way representing the real environments.

According to MIL-STD-810 C (Fig. 3) two test levels are provided, a functional- and an endurance test level. The prediction method is based upon aerodynamic or jet engine induced vibration. The test level of endurance test can be varied by equivalent variation of test time. Equipment need not function properly during the endurance test, but must perform properly at functional test levels. In accordance to BS 3G.100, the mission times and vibration categories of all ground and flight conditions are estimated and accumulated to give the equivalent of not more than 50 hrs testing at the most severe vibration category, throughout the equipment must function. Different test spectrum levels are associated with different flight conditions which can occur and associated durations can be related to the expected mission profiles. The duration of testing is related to test spectrum level via equivalent damage concepts, although the associated power laws differ in detail between American- and British Standards.

$$\text{MIL-STD-810 C} \quad : \quad t_2 = t_1 \cdot \left(\frac{W_1}{W_2}\right)^4$$

$$\text{BS 3G. 100} \quad : \quad t_2 = t_1 \cdot \left(\frac{W_1}{W_2}\right)^{2.5}$$

t = test time, W = test level PSD (G^2/Hz)

Options of narrow band random or sinusoidal test procedures (cycling or dwell) have been retained in British Standards. In case of sinusoidal test method the associated test level definition is related to the broadband random test level by assuming equivalent fatigue damage in some resonant part of equipment. These examples illuminate the difficulties of interchangeability of equipment, qualified to different Standard.

3. SOME TEST EXPERIENCE AND PROBLEMS IN VIBRATION QUALIFICATION

Equipment Vibration Tests

Most of this qualification experience relates to sinusoidal testing, which was performed as summarized in Fig. 1. The criteria for the selection of test levels are relatively vague and no account is taken of specific secondary A/C structure like shelves, trays or platforms. Specified test levels are defined as equipment input levels (that is,at attachment points to the A/C structure).

Fig. 4 shows a typical example of equipment, mounted on shelves.

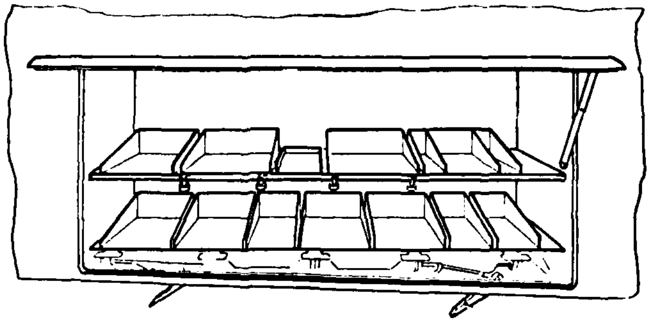

FIG. 4 EXAMPLE OF ELECTRONIC EQUIPMENT BAY

Fig. 5 is an example of platform mounted equipment.

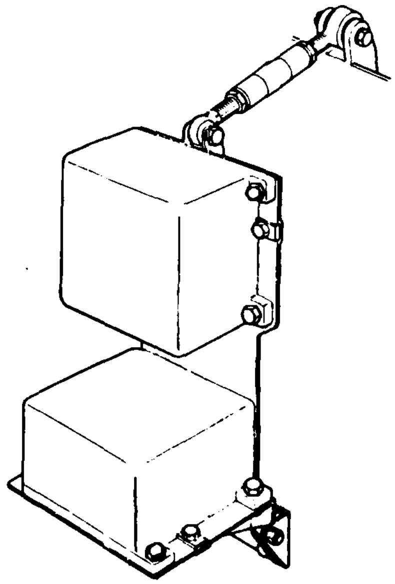

FIG. 5 PLATFORM-MOUNTED EQUIPMENT

According MIL STD 810, Method 514, the test item shall be attached "by its normal mounting means, either directly to the vibration exciter or by means of a rigid fixture" [1] . This input reference does not recognize the dynamic effects of equipment mounting structure and therefore many table tests featuring resonance dwell have poor similarity to the dynamic equipment behaviour in the A/C.

As a specific example, a vibration test with a hydraulic control actuator illustrates a severe problem of resonance dwell testing. A lateral bending vibration mode of the extended actuator at 118 Hz revealed an amplification factor of $\sim$10 (10g input and 97g output at the actuator body) and a potential fatique problem. A test level reduction was necessary and an inflight vibration survey has been required to confirm the adequacy of this vibration qualification. Measurements showed a maximum overall RMS value - OARMS 5 - 400 Hz of $\leq$1,2 g and no resonance excitation.

Equipment on Antivibration Mounts

The features of antivibration mounts for equipment mounting are shown in Fig. 6.

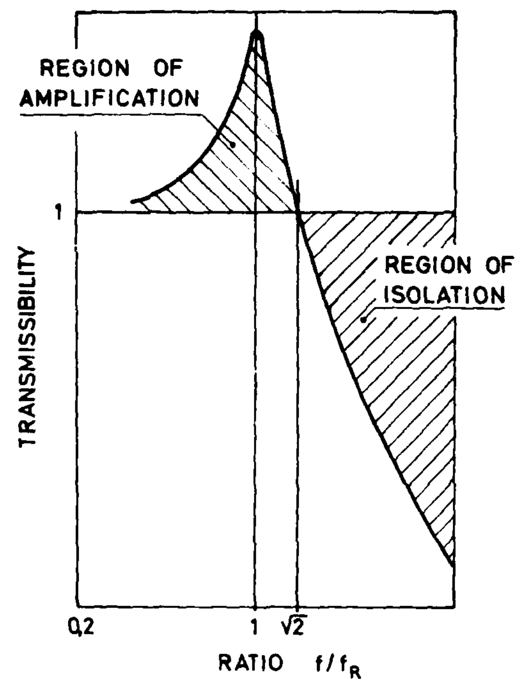

FIG. 6 TRANSMISSIBILITY OF ANTIVIBRATION MOUNTS

In the case of sinusoidal testing, the region of amplification in the low frequency range generally creates the main difficulties.

Available space, limited AV-mount amplitudes and superimposed static deflections have to be considered during the lay out of AVM support, in respect to table tests and intended use. Test time compression and continuous testing without stops is not a suitable or realistic procedure in respect to AV-mount fatigue together with heating or temperature problems due to high damping energy. These are unrepresentative of flight.

Many practicable AV-mount designs cannot fully satisfy the requirements of the sinusoidal test procedure as specified in MIL 810 B, Method 514.

The use of random test procedure in qualification tests will avoid these "table test related" problems associated with resonance endurance.

Vibration Tests on Combined Equipments

A combination of equipments, for example subsystems connected to a common airframe mounted primary equipment creates many problems concerning test philosophy and environmental simulation. There are difficulties in making a reasonable interpretation and application of existing specifications for combined systems. A characteristic arrangement is shown in Fig. 7.

Here, a gearbox carries subsystems, like generator, hydraulic pump and other equipment. This equipment combination is attached to the aircraft structure by means of links and direct bearing points. In- or outcoming power is transmitted by shafts, crossdrives, hydraulic- and electric lines.

Different sources of excitation contribute to the vibration environment for each item of equipment:

- excitation transmitted from A/C structure via attachment points
- excitation due to running systems (Gearbox, shafts, subunits)
- hydraulic pump ripples

These inputs will be modified by the dynamic behaviour of the combined system, and representation of the real environment is very difficult. In the recent past simulation has been attempted by conducting component- and assembled system vibration tests on a shaker, complemented by tests in a "functioning rig".

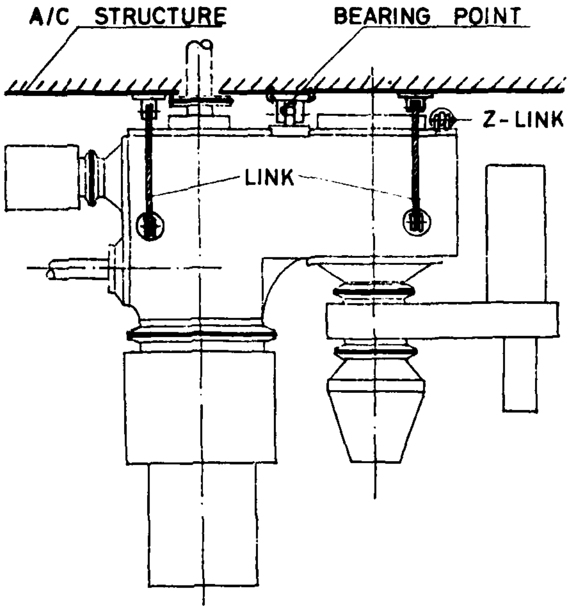

FIG. 7 COMBINATION OF EQUIPMENT

As an example of the influence of attachment structure, a system fundamental attachment vibration mode frequency was found to be 56 Hz in table test and 34 Hz in the real A/C mounting. Amplification factors in this mode were also different, up to 12 for table test and up to 8 for the real A/C mounting. These numbers indicate the difficulties in achieving realistic environmental simulation at representative conditions for the assembled system and the need to define input levels for individual component tests. To reach more uniform "philosophy" and test procedures is of great interest.

Vibration Tests for External Stores

Measured vibration environments on stores generally indicate predominantly random signal nature, modified by the dynamic characteristics of aircraft- and store structural modes. A wide variation in vibration environments has been found, strongly dependent on flight conditions. To establish useful qualification tests, considerable engineering judgement is required. In the recent past, sinusoidal and random test procedures have been applied, to show structural integrity. Test methods, very similar to equipment tests have been used calling for a "rigid store attachment" to the table and "taking" the store attachment points as the input reference. A more realistic store test procedure has been introduced in MIL-STD.-810 C, Method 514. The main points of this new procedure are the introduction of random tests, the reference to store response levels at nose and rear section and improved mounting methods.

Good test experience has been gained with the new procedure, applied in a test for a missile/launcher configuration. Fig. 8 shows, in the left diagram, an example of the determination of resonance peaks. The table input is random noise, the level is 6 dB lower than the calculated test spectrum for nose section of store. Resonances per definition are all peaks in store response spectrum (output spectrum) which exceed + 6 dB of input.

For functional and endurance test, level adjustment is limited to resonances and only these resonance outputs must reach the specified levels in the spectrum.

Tank Slosh- and Vibration Tests

This test appears basically sound in concept, since it provides some confidence in structural integrity of the fuel tanks under the unique combination of slosh and vibration loadings. Since sloshing can only occur at intermediate fuel states and forces increase with fuel contents the 2/3 full fuel state specified seems reasonable. Less clear is the insistence on slosh testing at 0.3 Hz and simultanous vibration (endurance) testing at 33.3 Hz. According the specification [6] an input double amplitude of 0.02 inch at the attachment points of the tank, and an average amplitude between the top and bottom of the tank at the "supporting bulkheads" of a minimum of 0.032 inch are required for the vibration test.

Amplitudes and stresses induced depend considerably upon the proximity of the tank fundamental bending mode frequency to the test frequency (33.3 Hz) and the mode shape. Therefore the requirements should be influenced by this dynamic behaviour of the tank.

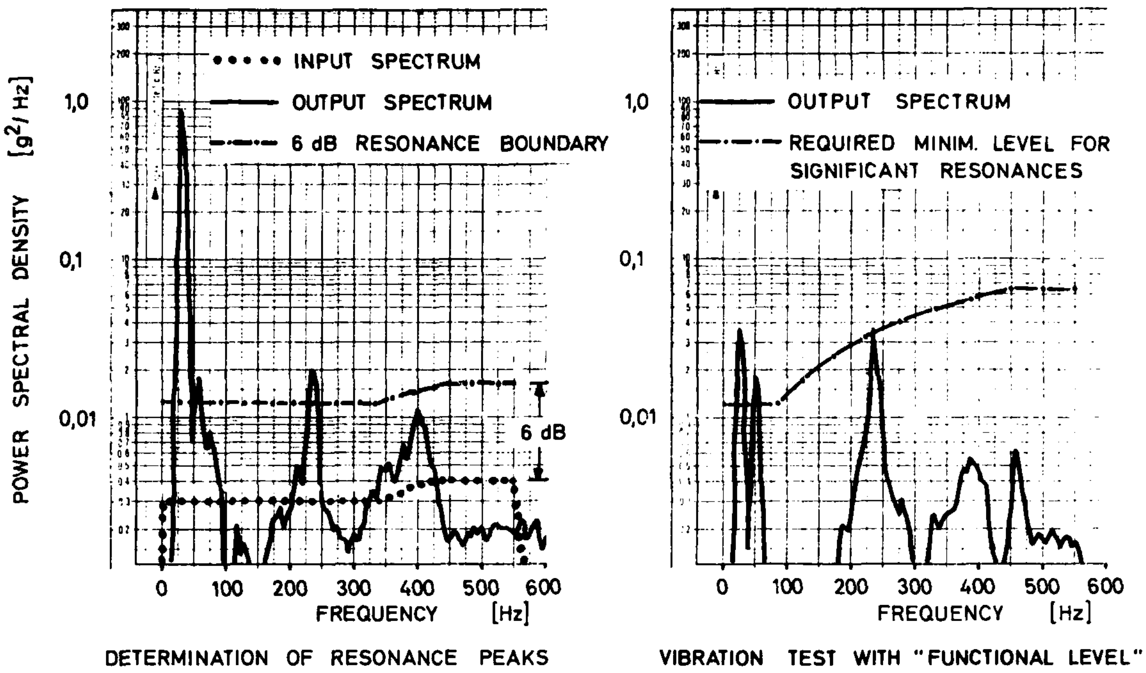

FIG. 8 VIBRATION QUALIFICATION FOR EXTERNAL STORES

Fig. 9 shows an example for reference points and measured fundamental bending mode.

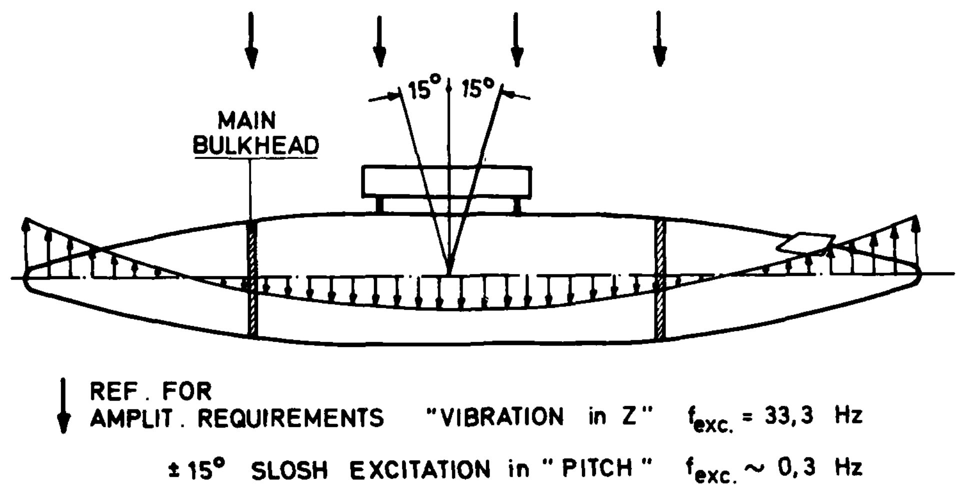

FIG. 9 TANK SLOSH AND VIBRATION TEST

In the shown case, the requirement of minimum average amplitudes at the supporting bulkheads was changed to "amplitudes shall be monitored" [7].

A more accurate definition of test conditions (frequency and amplitude) should be provided in this specification [6] taking into account the results of frequency-and modes search. Also necessary testing of high frequency vibration environment of tank and fins should be mentioned. More failure statistic from qualification test and A/C use is of further interest, when a closer simulation of real environment is intended.

Characteristic acceleration time histories measured at primary structure are shown in Fig. 10.

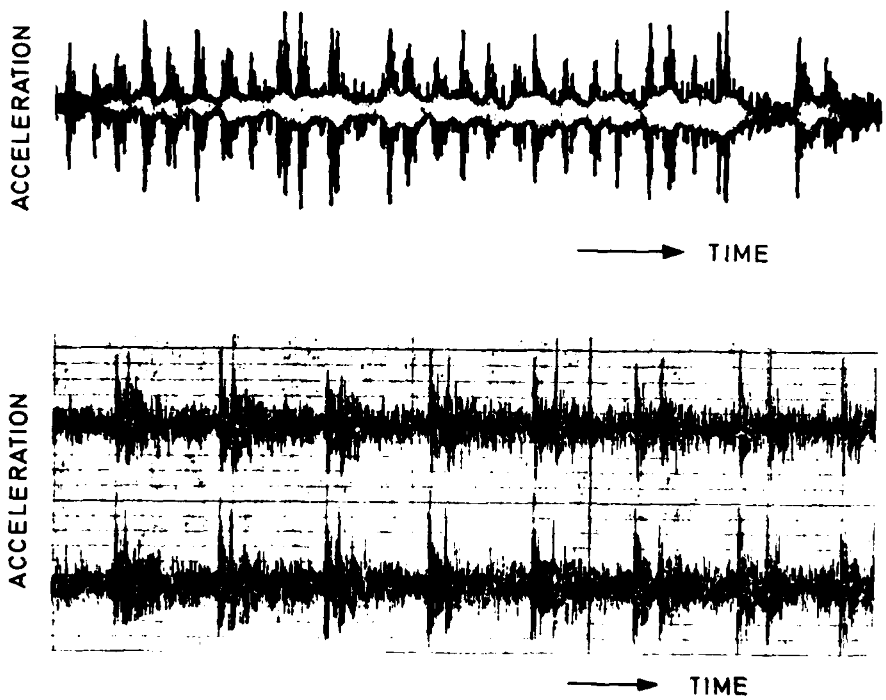

FIG. 10 TIME HISTORIES OF IMPULSE-EXCITED A/C STRUCTURE

These time histories indicate the typical signal nature of such environment, that is a combination of a nearly periodic impulse sequence of gunfire or similar source and random background. Such behaviour is influenced principally by variations in firing rate, by not synchronized firing of left- and right hand gun, and by reflected excitation. The equipment and gun mounting-and connecting airframe structure have also a strong influence on equipment dynamic response to this excitation.

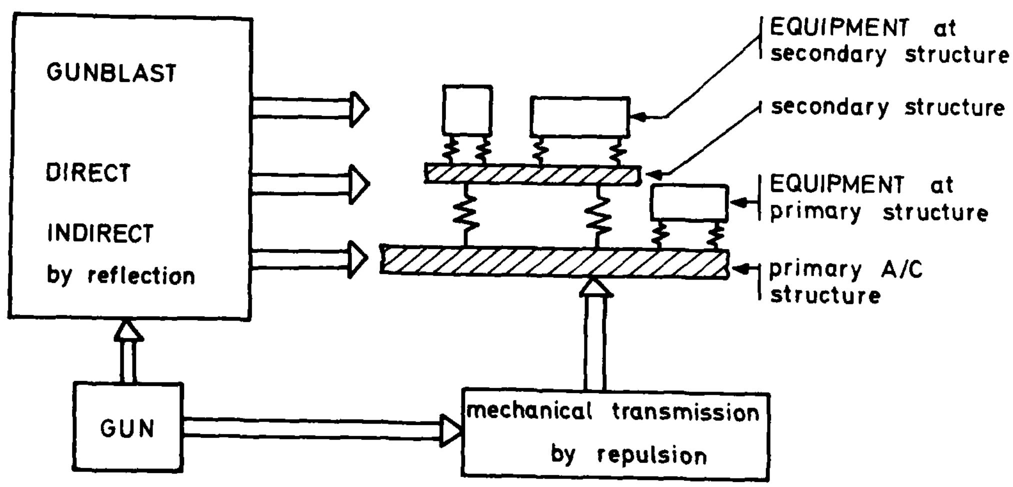

FIG. 11 SOURCES OF EXCITATION AND KINDS OF STRUCTURE

In MIL-STD.-810 C, Method 519, for instance, specific transfer functions are introduced and used in the method of level prediction.

The available observation time for gunfire data analysis is very short in respect to statistic analysis requirements. However, a representation of adequate test environment is required.

Analysis technique and methods of shaker control are of great significance in this approach.

Several investigations are known, which aim for practicable methods of analysis and an understanding of limitations introduced in the analysis under particular circumstances and hence to provide a reasonable basis for table test simulation.

A sufficient description, in the general case, should consist of:

- Time histories, showing real peak values within defined frequency band
- Power spectrum (broadband analysis Δf 10 Hz up to 2000 Hz)
- Power spectrum (narrow band analysis Δf 1 Hz up to 250 Hz)
- Cumulative spectrum from which the overall mean square value (OAMSV) and the overall root mean square value (OARMS) can be defined for a desired frequency band.

Fig. 12 shows an example of power spectrum and cumulative spectrum.

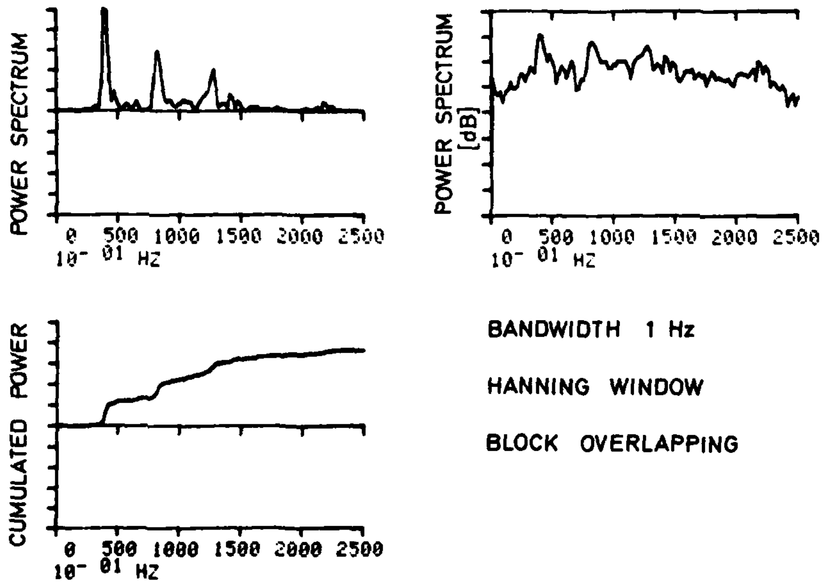

FIG. 12 EXAMPLE OF NARROWBAND ANALYSIS

Methods of averaging in frequency domain are helpful to make optimal use of given data information, when digital analysis equipment (Fourier Analyzer) is employed.

From these data and relevant energy-considerations a composite test spectrum of sinusoids and random can be produced, corresponding to that in MIL-STD.-810 C. Method 519, see Fig. 13.

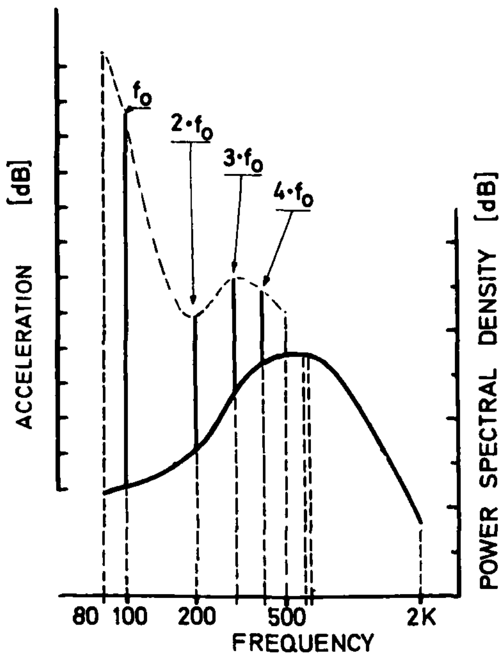

FIG. 13 COMPOSITE SPECTRUM FOR GUNFIRE-QUALIFICATION

The simulation of composite spectra as specified in [1] is not yet a common technique in test laboratories. Especially the sweep requirement is a problem in case of digital table control equipment. The lack of phase representation in this method is subject to considerable discussions. Corresponding investigations at RAE-Farnborough are concentrating to reproduce the real acceleration time history [10]. Another approach of simulation of complex wave periodic vibration was undertaken at Hughes Aircraft Company [11].

4. MEANS OF IMPROVEMENT AND RECOMMENDATIONS

The evidence presented shows that existing qualification procedures or their application have to be improved in many respects. Greater realism can only be achieved by more feedback from aircraft- and laboratory experience and broader information exchange including analytical background. Possible improvements can be foreseen in the following areas, all of which should lead to increase equipment reliability in service:

Vibration Environment

Vibration measurements of real environments are of great interest with respect to better environment prediction. Extensive vibration measurements on a wide variety of military aircraft should be gathered together to provide an up to date review of dynamic environment. These data can be used to resolve questions concerning the realism of test levels and durations in laboratory qualification tests.

The introduction of transfer functions, representing the dynamic equipment airframe interface as used in MIL-STD-810 C, Method 519, is a very interesting step to improve methods of environment prediction.

Methods of Environment Analysis

Uniform and specificially adapted methods of data analysis and "environment description" are necessary for the intended purpose. Gunfire environment analysis can be taken as an example of the need for this. A possible basis for this is Ref.[13].

Table Test Simulation

To allow a realistic simulation of vibration environment, the necessary table test capabilities and equipment monitoring facilities must be provided. Whilst some facilities do exist for random testing (indeed for combined random sinusoidal testing for gunfire simulation) the data do not always coexist with the usually extensive facilities needed to monitor equipment functioning during vibration tests.

Appliers should be encouraged to introduce the necessary facilities. This is important in respect to improved component design.

Component Failure Modes

It is widely assumed that fatigue is the only mode of failure in equipment unreliability. Whilst this is probably true in the long term there is no doubt that other modes may dominate in the short term. For example, difficulties may lead to incorrect installation and premature failure. No amount of rig testing in the correctly installed state will reveal this. Such problems can occur with store carriage and emphasize the need to consider what will happen in real life situations, not merely in the laboratory environment. A comprehensive review of equipment failure modes should provide a more appropriate definition of the frequency range which must be reproduced in rig tests.

Component Design

It is clear that many equipment fatigue failures which occur are due to mounting design features which emphasize vibration, for example these are too few or poorly sited or too flimsy. In addition, the use of vibration resistant features should be more widely adopted (for example, crimped rather than soldered connections). Whilst such features are primarily the responsibility of equipment suppliers, wider dissemination of vibration qualification test experience of such matters would be to the long term advantage of all.

General Philosophy

Whilst more realism in qualification is desirable, it is obvious that in reality all of these features of exact simulation will never be realized. Sophisticated methods of level accumulation, spectral-enveloping/smoothing and test time compression are the common way to achieve feasible simulation in laboratories. In addition, effects of nonlinear system behaviour, simultaneous three axis vibrations as well as accumulated test environment (vibration-, shock-, gunfire test), applied to the same test specimen,should be considered. A measure of overtesting is probably useful in such cases, where equipment will be able to withstand these conditions and if such overtesting allows more general standardisation and wider interchangeability of equipment for operators.

RECOMMENDATION

Coordinated international activity in this field is believed to be of importance and benefit to all concerned and is firmly recommended.

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CIVIL AIRCRAFT

EQUIPMENT ENVIRONMENT QUALIFICATION TECHNIQUES

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SUMMARY

In Civil Aviation there is already very considerable international agreement on the environmental testing of aircraft equipment.

This paper discusses the way in which we have viewed the vibration testing of aircraft equipment and our experience in producing, with our French partners, the procurement document for Concorde and the proof of its use in service. The paper finally presents the environmental test levels that are in existing international requirements for civil aircraft.

1.0 INTRODUCTION

In the deliberations of the 47th Meeting of the Structures and Materials Panel the proposed Terms of Reference for a Working Group on "Dynamic Environmental Qualification Techniques" were submitted by Professor Forsching. The opinion was expressed that the activities should not only be confined to military aircraft, but should also be extended to civil aircraft, missiles and spacecraft.

In Civil Aviation there is already very considerable international agreement on the environmental testing of aircraft equipment. This Spring sees the culmination of a round of international negotiations on the up-dating of the transatlantic document DO160/ED14, and there is now four years experience of its widespread use both in the United States, and in Europe.

It is necessary to define two categories of equipment:-

Category I: Equipment very important to the safety of the aircraft

Category II: Equipment less important to the safety of the aircraft, where the intention is to demonstrate the ability of the equipment to function within specification limits when subjected to representative flight vibration levels, and that the equipment is sufficiently robust.

2.0 VIBRATION TESTING OF EQUIPMENT

2.1 Category I

Equipment in this category is very important to the safety of the aircraft. Equipments would be tested at the flight vibration levels for a considerable time and in certain cases even up to the life of the airframe.

Because of the considerable times involved, accelerated level testing, see Fig.1, is both desirable and acceptable. The philosophy behind the acceptance of such accelerated testing will be discussed later, when dealing with the Current Civil Requirements (Para.5.0).

2.2 Category II

The bulk of aircraft equipment falls into this category. Our aim is to show that equipment in this category can reasonably be expected to have an operational life comparable to the basic airframe. Any test of a piece of equipment made up of many different materials will, of course, have component parts having different fatigue characteristics, but by passing the vibration test the equipment will have been shown to have a certain 'robustness'.

In the Concorde Mechanical Vibration Document, (colloquially known as Test 17) three alternative test procedures are given. They are, in order of preference:

(a) Broad band random
(b) Sine Wave
(c) Narrow band random

2.3 Test Procedures

Test procedures follow the pattern:-

1) Static performance test.
2) Initial resonance search in each of the three axes.
3a) Endurance test in first axis.
3b) Endurance test in second axis.
3c) Endurance test in third axis.
4) Final resonance search in each of the three axes.
5) Static performance test and visual examination.

The test duration for all 3 procedures is 20 hours each along the aircraft lateral and vertical axes and 10 hours in the longitudinal direction.

For the endurance test broad band random testing is now generally preferred by the specification writers and the testers of equipment, on the assumption that it more closely represents the conditions in flight where all frequencies are excited. On the other hand failures in aircraft equipments due to vibration may, in general, be attributed to fatigue. The major stresses which cause such fatigue occur at a resonance of the system and it may be assumed that such equipment failures therefore generally occur at a resonance. Therefore an endurance test, just at the resonances of the system, should be sufficient to determine an equipments "life". The problems are, however, determining all of the resonances, and estimating the vibration levels of the environment and the equivalent fatigue damage. Arguments will continue, and in the meantime a need is established for the two test approaches.

It must be recognised that a large number of aircraft equipment manufacturers do not have random motion test equipment, nor have they ready access to it. Although there is no direct sinusoidal equivalent to a random motion test, it is essential, for practical reasons, to have a sinusoidal test of approximately the same severity. The way in which the sine test levels can be derived from the spectra used in the random motion test have been dealt with in a number of papers (see for example Refs. 1,2,3). A number of practical empirical formulae have been proposed and most of these are based on equating the responses of lightly damped simple single degree of freedom systems to sine and random input. The generally accepted formula is (as shown in Fig.2):

$$g = k\sqrt{\frac{\pi SF}{2Q}} \qquad \text{in which}$$

g = peak acceleration of the sinusoidal test
k = a constant, $k = 3.8$ as suggested by Mr. Gaukroger (Ref.3)
S = acceleration spectral density (g^2/Hz)
F = frequency considered
Q = magnification factor at resonance
$Q = 2.5$ for $F \leq 44$ Hz

Alternative laws with basic formulae have been compared by Danel (Ref.4) in a paper in which he examines a number of earlier synthesis papers, for example Refs.3,5, and proposes some new spectra for international consideration.

3.0 CONCORDE EXPERIENCE

3.1 Test Specification

The Concorde aircraft was split down into seven regions, A through G, as shown in Fig.3 each with its broad band, narrow band and sine test spectra. We show, as an example, in Fig.4A, the test spectra for the forward and rearmost portions of the fuselage, regions 'C' and 'F', illustrating the allowance that has been made for acoustic noise aft of the jet efflux. Fig.4B is the equivalent for sine wave endurance testing in regions 'C' and 'F'.

3.2 Flight Measurements

During the development flying of Concorde, measurements were made of the accelerations on both the structure and the equipment. The test level spectra have been vindicated for all regions of the aircraft except for the extreme rearmost tip of the fuselage, the location of the anticollision light, where the flight environment is much more severe than in the original specification. Fig.5 shows the broad band random vibration spectra for the lengthened rear fuselage of the production Concorde aircraft.

In the forward fuselage, for equipment mounted internally away from the fuselage skin, the test levels are slightly higher than those measured on the aircraft.

4.0 INTERNATIONAL REQUIREMENTS FOR CIVIL AIRCRAFT

4.1 In 1975 agreement was reached between RTCA (the Radio Technical Commission for Aeronautics) in the U.S. and EUROCAE (the European Organisation for Civil Aviation Electronics) on a joint document covering Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments (RTCA DO-160/ EUROCAE ED.14) (see Fig.6).

4.2 World-wide civil aviation interests in this field are provided by I.S.O. (the International Standards Organisation). At a meeting in London, in October 1977, almost identical resolutions came from the U.S.A., and French delegation proposing the preparation of a comprehensive standard for the environmental and operating test conditions for aerospace equipment.

It was proposed that document DO-160/ED.14 (1975) should be used, but with the introductory statements revised so that the document would be applicable to all items of aircraft equipment. Imminent changes being considered for the document would be incorporated.

4.3 Following the London I.S.O. meeting the R.T.C.A. formed a special committee, SC-135, to revise DO-160/ED.14 and this included members of EUROCAE, and a full meeting of the committee was held in July 1978 in Wahsington.

For vibration, it was agreed to include the change in the Flight Vibration Level for Rack Mounted Equipment proposed by EUROCAE and substantiated by flight measurements made on a variety of U.S.A., and European civil jet aircraft. The results of the measurements are reported Ref.6 (and discussed below Para.5.2).

Most importantly, the meeting agreed to adopt the addition of an optional Accelerated Level Test when a more severe environment is required. It is derived in a similar manner to MIL-STD-810C and was adopted on the understanding that these tests would be used primarily for mechanical equipment and that the existing tests and RTCA/Federal Aviation Agency agreements would continue in force for electronic and electrical equipment. The full change proposal has now been agreed by correspondence between the vibration specialists and will have been presented for approval by the full meeting of SC-135 in Washington last week.

This revised document will be considered for adoption as an I.S.O. standard.

5.0 CURRENT CIVIL REQUIREMENTS

5.1 Standard Flight Levels and Severe Levels

United States industry has to show that aircraft equipment has met the Legal Minimum Standard required by the FAA who licence the RTCA to administer the system for clearing electrical and electronic equipment and instruments. The DO-160/ED14, of February 1975, fulfilled this requirement but now, after four years successful application of this document, without any changes to its text, an updating and enhancement is planned, as mentioned above.

In the new edition, the scope of the document has been widened to include its application to all aircraft equipment, electrical and non-electrical alike. The chapter on vibration now includes an optional Accelerated Level Test which may be called for in a procurement document whilst maintaining the original Flight Level Test which is required for testing Electrical and Electronic Equipment to the FAA minimum performance standards.

It is our view that the airframe manufacturer should define the environment test levels that are to be used to represent conditions in aircraft. We consider that, for procurement, equipment of all kinds for commercial aircraft should not just pass the Minimum Performance Requirements, but should show some proof of their general 'robustness' and ability to perform within specification limits during a prolonged period of testing at the anticipated aircraft vibration levels.

In the past the concepts of 'minimum performance' and 'verification of life' have lead to the adoption of test spectra which have been incompatible, even as regards the frequency range adopted for a given region of an aircraft. It is desirable to have test spectra where the more severe cases envelop the less severe and enable any equipment which has passed the more severe test to automatically pass the less severe requirements. This situation can best be achieved by establishing the flight levels and using these for all tests, varying the test time to alter the severity. Where this would lead to unreasonably long test times the principle of accelerated testing should be used. The new 1979 issue of DO-160/ED14 will reflect these concepts of testing.

DO-160/ED14 specified a Standard Vibration Environment, for three types of aircraft

Helicopters
Fixed wing - turbo-jet and turbo-fan engined
Fixed wing - reciprocating and propeller-turbine engined

and a Severe Vibration Environment for

Fixed wing - turbo-jet and turbo-fan engined aircraft

Confining ourselves to the turbo-jet, turbo fan aircraft we can examine the spectra given in DO-160/ED14. Fig.7A shows the standard broad band random spectra, and Fig.7B shows the standard levels for sine-sweep testing based on the equivalent broad band random spectra. Fig.8A shows the equivalent severe vibration spectra where these have been based on a full-life accelerated test of 3 hours duration, and Fig.8B gives the corresponding sine sweep severe vibration levels to be used in a 3 hour test.

The standard levels have been in existence for a long time, and have given good service, but their derivation is now lost in obscurity.

5.2 Rack Mounted Equipment

Verification of flight vibration levels is a lengthy and expensive business, but, as mentioned earlier, a very thorough evaluation was made by the UK, between 1973 and 1976, of the flight vibration level of rack mounted equipment. This involved measurements, on flights within Europe and across the North Atlantic, of the vibration in 3 axes on nine commercial aircraft over at least 4 flight sectors each comprising 7 phases of flight. This considerable undertaking was instigated by the equipment manufacturers who wished to have measured levels for inclusion in the British Standards. The results of these measurements, Ref.6, have now been incorporated in BS 3G100 and DO-160/ED14. Fig.9 shows, overlayed on some existing specifications, the overall envelope with the exclusion of the 747 and Trident aircraft, as the racks of these aircraft were considered to be unacceptably flexible for this exercise.

5.3 Accelerated Testing

The severe levels in DO-160 have been based on the accelerated testing concepts summarised by Danel (Ref.4). A stress limit of fatigue value of 2×10^7 reversals and an oligocylic stress of 3 x 10^3 reversals has been chosen, see Fig.10. Then assuming:-

T_{BBR} (Broad Band Random Time) $\triangleq$ T_{SW} (Sine Sweep Time)
= $40T_s$ (Sine dwell at a given frequency) = T_D (Test duration per axis, in seconds)

the ratio, k_s, of the accelerated 'g' to flight 'g' can be evaluated and is as shown in Fig.10. Assuming a test time of 3 hours per axis for the accelerated tests, as in MIL-STD-810c, k_s can vary from 1 to 3. When the same S/N curve is considered in relation to broad band random testing the acceleration factor, kr, is shown to be equal to $(k_s)^2$, thus giving values of k_R between 1 and 9.

6.0 CONCLUSIONS AND RECOMMENDATIONS

In general, the test specifications drawn up for use in commercial applications have proved to be adequate, although detailed records and analysis of failure rates due to the vibration environment are not available. There has been satisfaction in the civil field with the use of DO-160/ED14 as a minimum performance document for electrical and electronic equipment and instruments, and it is planned to extend the document to cover all items of aircraft equipment, and to introduce a more severe level of vibration considered necessary for procurement requirements. This document will be considered for adoption by ISO.

If this AGARD Working Group is to continue with the examination of Dynamic Environment Qualification Techniques it should be borne in mind that it will be economical for equipment suppliers and airframe manufacturers alike to have as much commonality as possible between the military and civil aircraft test philosophies and test spectra.

Full examination of the work done in producing the civil document could form a useful first "stepping stone" in the evolution of any common military specifications.

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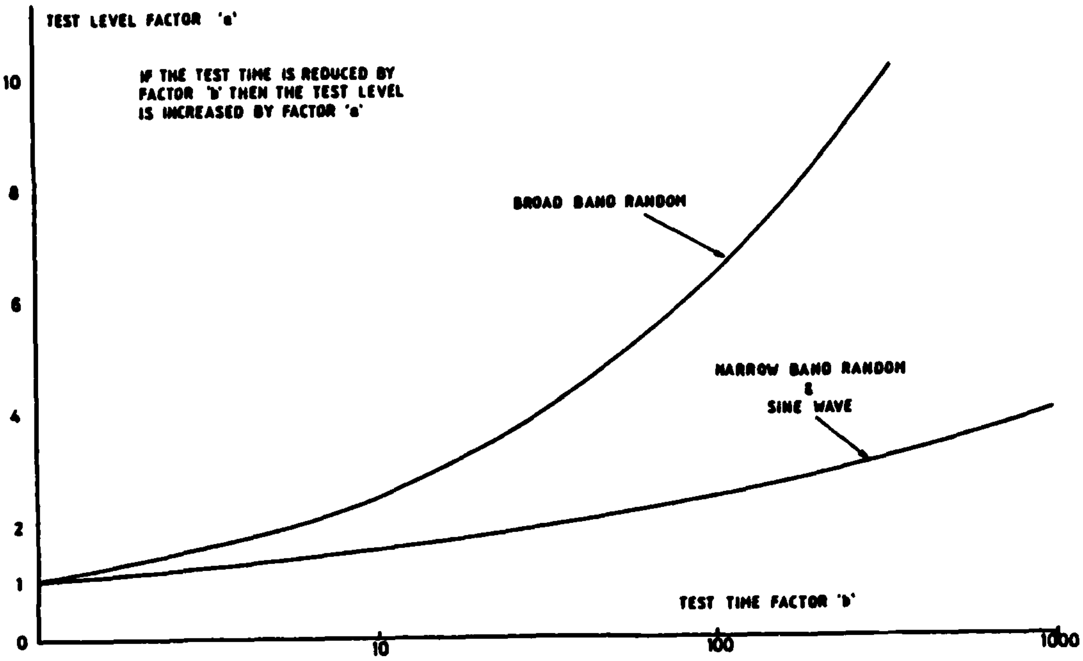
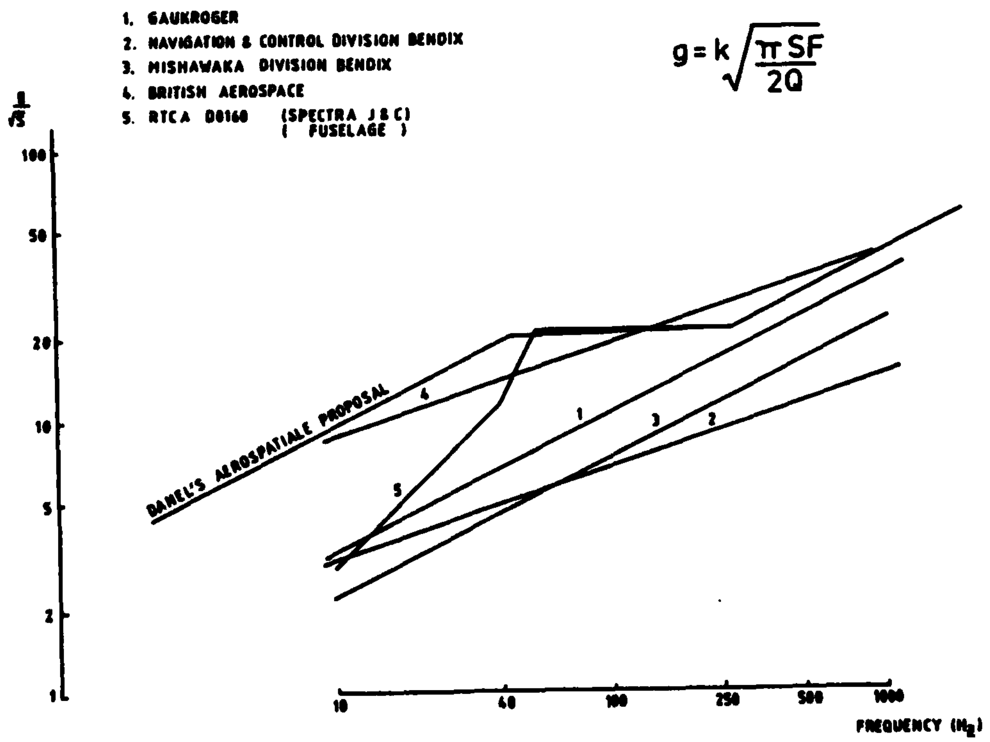
TEST TIME REDUCTION CURVE

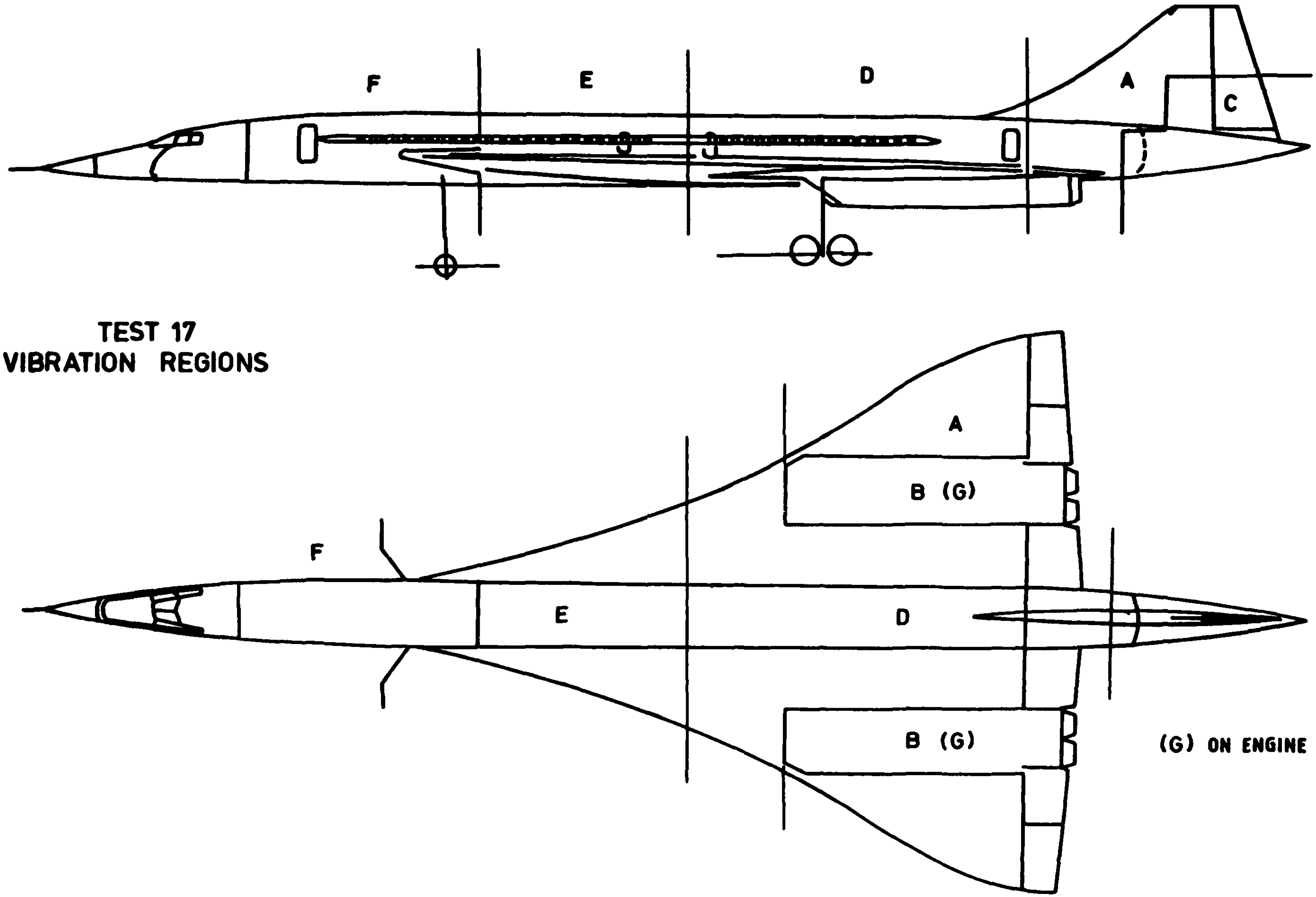
FIG. 1



RELATIONSHIP BETWEEN SINE & BROAD BAND RANDOM VIBRATION

FIG. 2





TEST 17
VIBRATION REGIONS

FIG. 4

CONCORDE VIBRATION SPECTRA

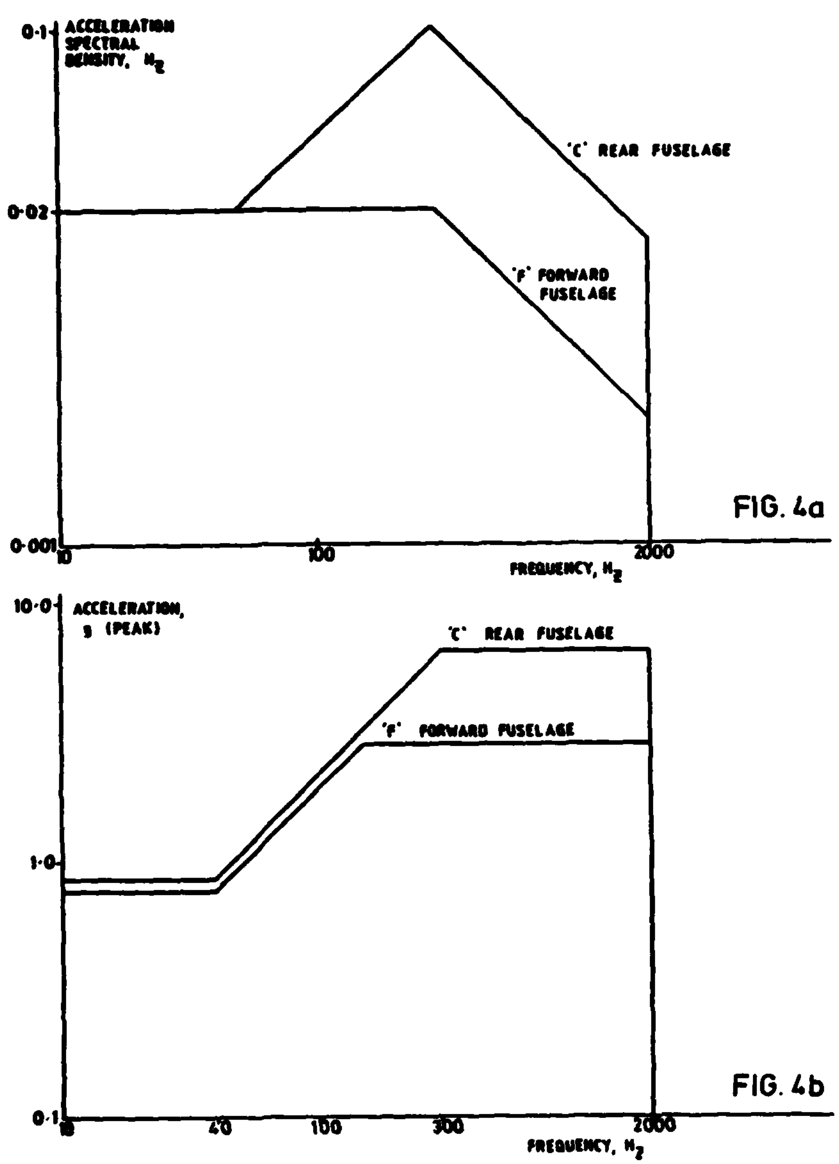
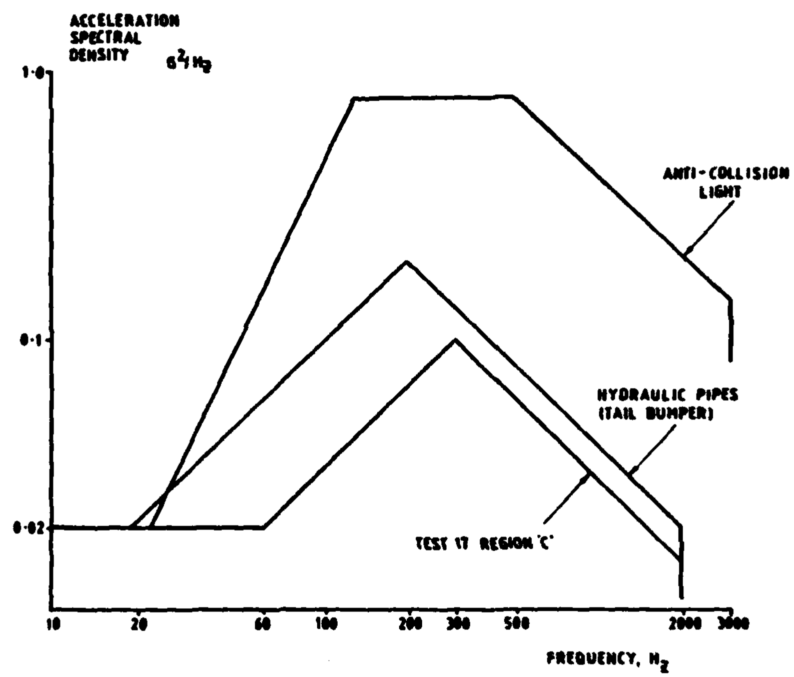


FIG. 5

VIBRATION SPECTRA FOR CONCORDE TAIL CONE



AIRCRAFT ELECTRICAL EQUIPMENT

U.S.A : Radio Technical Commission for Aeronautics.

EUROPE : European Organisation for Civil Aviation Electronics

U.S.A

DO-138

RTCA SC-135

DO-160/ED14

EUROPE

RTCA

in English

EUROCAE

in English & French

identical wording

Environmental Conditions & Test Procedures for Airborne Equipment

DO-160 - defines the Legal Minimum Standard required by the F.A.A in U.S.A

- compliance does not necessarily establish life

RTCA / EUROCAE DO160 / ED14 FLIGHT LEVEL VIBRATION SPECTRA

FIG. 7

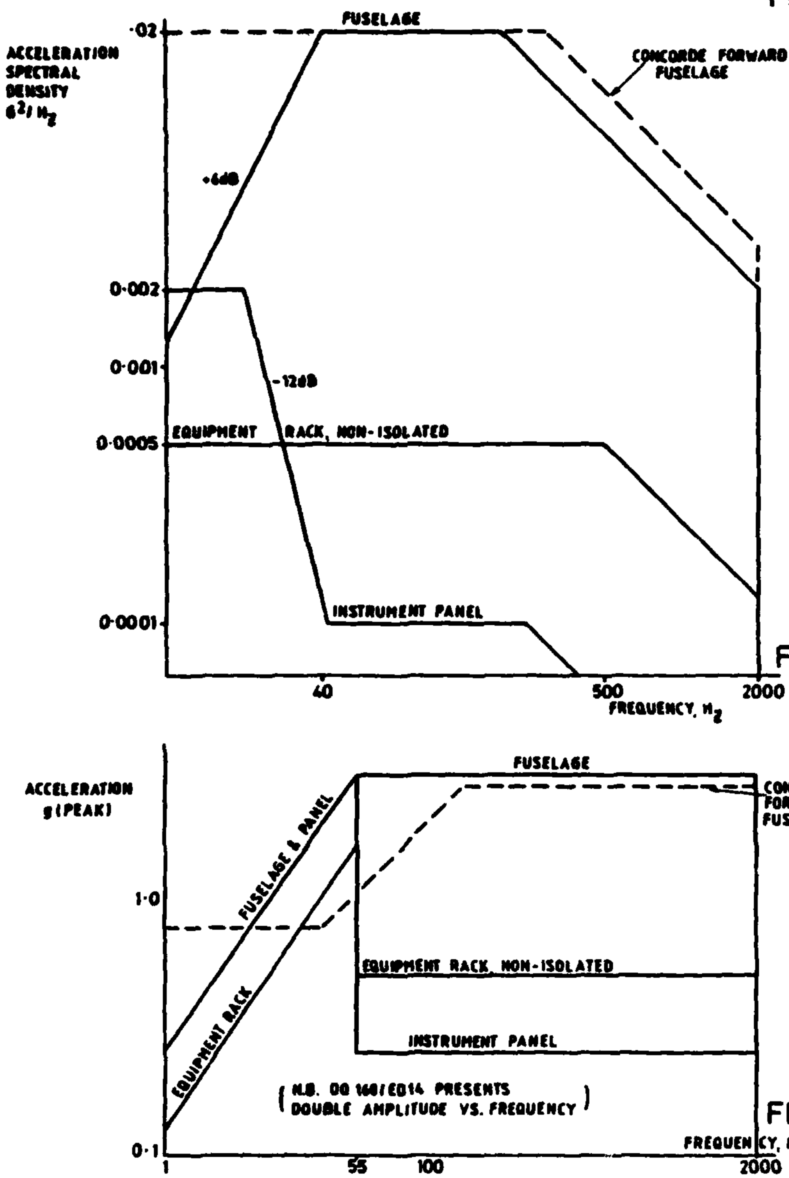


FIG.7a

FIG.7b

RTCA / EUROCAE DO160 / ED14
SEVERE LEVEL VIBRATION SPECTRA

FIG.8

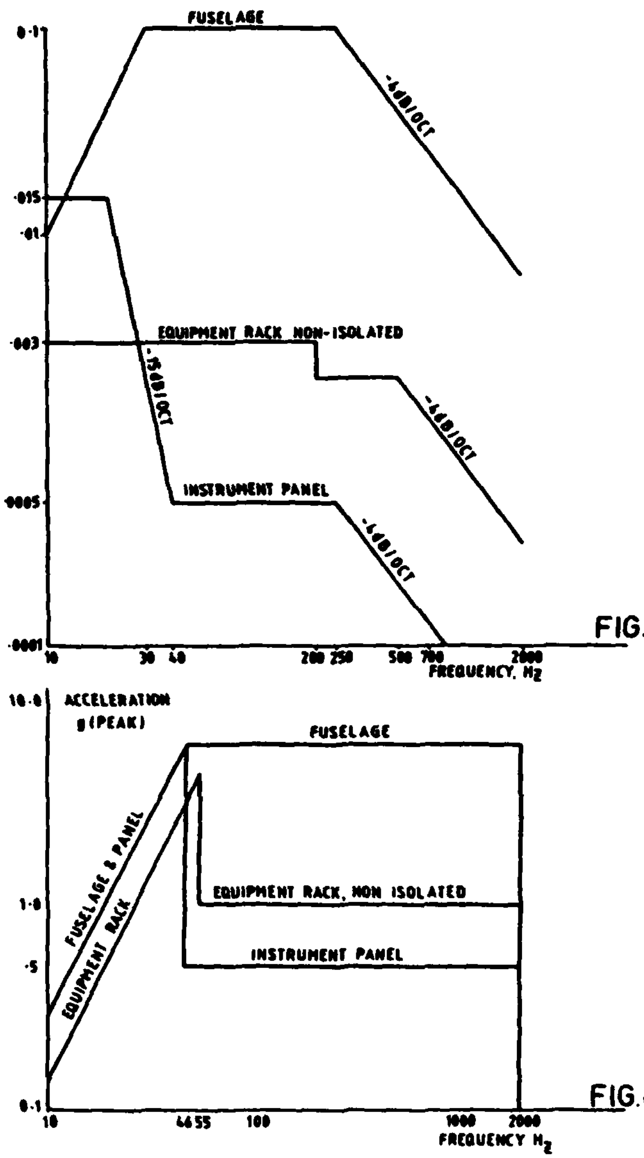


FIG.8a

FIG.8b

MEASURED SPECTRA ON EQUIPMENT RACKS IN CIVIL JET AIRCRAFT

FIG.9

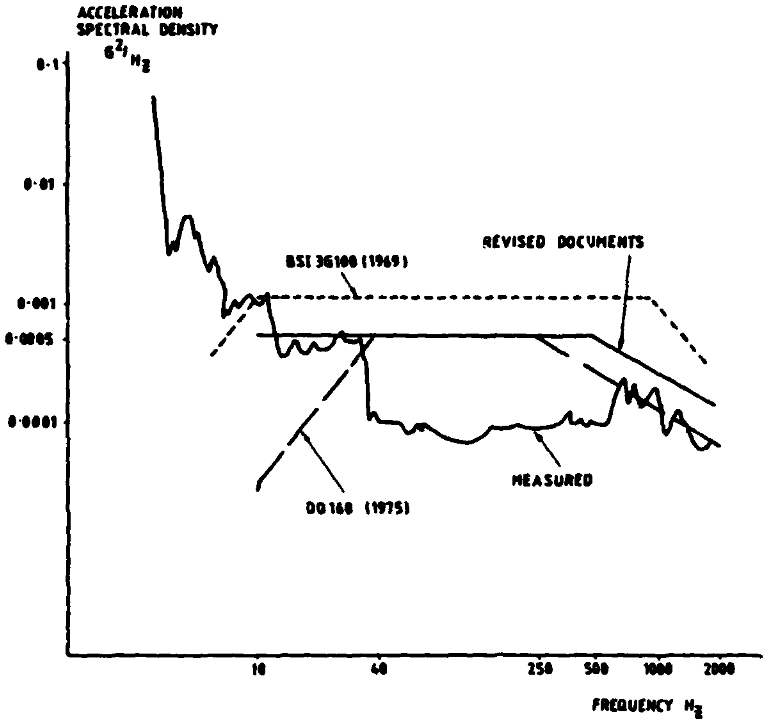
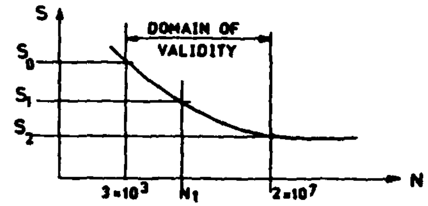


FIG. 10

$$S_1 = S_L\left(\frac{2\times10^7}{N_1}\right)^{1/8}$$

S_L - STRESS AT LIMIT OF FATIGUE ($N > 2\times10^7$)

S_1 - STRESS AT N_1 CYCLES ($3\times10^3 < N_1 < 2\times10^7$)



AT THE LOWER LIMIT $N = 3\times10^3$, THE CORRESPONDING S_0 STRESS APPROXIMATELY EQUALS ($\simeq$) 3 TIMES S_L

$1 < k_s < 3$

$$k_s = \frac{g_A}{g_F} = f(N_{TD}) = \left(\frac{2\times10^7}{N_{TD}}\right)^{1/8} = \left(\frac{8\times10^8}{T_D F}\right)^{1/8}$$

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14. Abstract

Dynamic qualification test procedures must be applied for proving the safety and reliability of aircraft and spacecraft structures, and for determining the resistance of equipment to the effects of induced environments peculiar to military operations and requirements. The first paper deals with the practical application of MIL-STD-810C to USAF aircraft procurements. In the second, test experiences and problems in vibration qualification are presented and some means for improvement are indicated and recommendations made. The third is devoted to problems of civil aircraft equipment environmental qualification techniques.

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